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# INTEGRATED GEOTECHNICAL AND STRUCTURAL APPROACHES FOR REDUCING SEISMIC VULNERABILITY OF HERITAGE BUILDINGS

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***Abstract***

*The paper outlines key characteristics of heritage buildings and explains why they require protection against strong seismic motions generated by the Vrancea source. One of the most common challenges these structures face is differential settlement during earthquakes; to mitigate this, several supplementary measures can be implemented. Resonant column or dynamic triaxial tests, used alongside standard geotechnical investigations, provide additional insight into soil behaviour. These methods focus on evaluating the variation of the shear modulus with strain, enabling a more accurate assessment of soil properties. The resulting data support the selection of appropriate interventions to improve site conditions and reduce the risk of structural damage during future major seismic events. Structural protection can also be enhanced through base-isolation techniques, applied according to site conditions and the specific characteristics of each building. This approach reduces seismic forces and modifies critical response parameters to safer levels. The paper highlights the advantages of these optional measures for safeguarding historical monuments and older administrative buildings, emphasizing both their technical effectiveness and their broader economic and social benefits.*

***Key words****: heritage buildings, seismic vulnerability, settlements, seismic isolation, resonant column.*

## INTRODUCTION

The protection and rehabilitation of heritage buildings include consideration of the impact of seismic movements affecting the soil deposit on which their foundation rest and the structure. The paper considers heritage buildings situated in Bucharest - capital of Romania - a city under the influence of Vrancea seismic region. This seismic source, the most important in Romania, in terms of magnitude, human and economic losses in the country, only in the last century has triggered 2 major earthquakes: November 10, 1940 with moment magnitude Mw = 7.7, approximately 600 victims, and March 4, 1977 with moment magnitude Mw = 7.4, approximately 1500 victims (Mărmureanu, 2020). The latter seismic event damaged and destroyed approximately 32900 buildings in Bucharest and in other parts of S-E of the country (Balan et al., 1982).

The paper focuses on some optional measures considered by structural designers during rehabilitation, necessary to mitigate the seismic vulnerability of these structures, beyond those imposed by the norms in force. First of them is an optional evaluation to be performed, after standard geotechnical studies were accomplished, and involves tests on resonant columns or dynamic triaxial. They allow to calculate geotechnical and rocks specific parameters, as they varying inside the soil deposit during strong seismic shakings. The reason of this evaluation is linked to the settlement phenomenon that may appear in the aftermath of a strong earthquake, for foundation of structures, especially if located on soft, sedimentary soils.

Situated in the central sector of the Vlăsia Plain - a sub-division of the broader Romanian Plain - Bucharest is located approximately 165 km from the Vrancea seismic zone. The region is geologically characterized by thick, unconsolidated sedimentary deposits. The local topography is heavily influenced by the Dâmbovița and Colentina rivers, which created distinct zones prone to natural erosion and alluvial sedimentation. Consequently, evaluating the geological, geotechnical, and hydrological properties of the local aquifer systems is essential for assessing the overall environmental and structural stability of the urban area.

These soil conditions can favour the development of ground settlements, either due to naturally soft soil layers or anthropogenic factors such as artificial fills. Identifying these zones and understanding the processes that

cause such soil behaviour is essential. Equally important is knowing what types of buildings occupy these areas, their structural systems, and whether they have undergone previous repairs or experienced past seismic events.

Settlements can introduce additional stresses into building structures, and during an earthquake these stresses may amplify damage, leading to cracks in structural elements, displacement of interior walls, or deterioration of floors and installations. Building vulnerability increases when settlement-induced stress is compounded by seismic stress from strong earthquakes.

Earthquakes generate seismic waves that propagate from the source through the geological environment and reach sediment layers. The soil material of the subsurface layers is subjected to seismic stresses equivalent to dynamic loads with variable levels of strain. The level of soil deformation depends on many parameters, such as: the event duration, maximum ground acceleration, number of wave cycles, type of waves, soil type, and depth.

When soils are subjected to time-dependent dynamic loading (e.g. earthquakes or vibrations), their deformation directly depends on the amplitude and repetition of the cyclic shear deformation (Ishihara, 1996; Braja & Ramana, 2011). The soil exhibits a transition to nonlinear behaviour at deformation ranges above $10^{-4}$-$10^{-2}$%, associated with the accumulation of permanent deformations. This leads to progressive crack widening and significant differential settlements. For deformation levels greater than $10^{-2}$ %, the soil configuration undergoes strong nonlinearity and elastoplastic deformation; structural bonds break, severely reducing soil cohesion. This reduction in internal strength results in soil sliding (shear failure), excessive compaction/consolidation, and increase in pore water pressure. This behaviour leads to soil instability, foundation settlement, and liquefaction during seismic loading (Bratosin, 2002; Yoshida, 2015). The degradation of soil stiffness and cyclic settlements induced by strong earthquakes can be significant in urban areas formed by granular soil types, and Bucharest is one of the cases (Vucetic & Dobri, 1991).

Earthquake-induced settlements should be considered separately for two cases, the one with structures and the other without structures on the surface of the ground. For the former: total incremental settlement $\Delta S_t = \Delta S_{is} + \Delta S_{cy\,s}$, where immediate settlement – immediately after earthquake is $\Delta S_{is}$, and due to dissipation of cyclic-induced excess pore pressures $\Delta S_{cy\,s}$.

Another optional measure to protect the construction from powerful forces inside it during a strong seismic event is to isolate the structure from the foundation through different methods (Apostol et al., 2017; Liu et al., 2014; Taniguchi et al., 2008). The paper points out the results of seismic-base isolation intervention, highlighting the monitoring buildings activity and data processing performance (Balan et al., 2020).

The benefits of these optional measures to protect heritage buildings from strong earthquakes are discussed.

## MATERIALS AND METHODS

An essential step at the start of any rehabilitation project is evaluating whether the existing soil deposit can safely support the additional loads introduced by the planned construction activities. To do this, it is advisable to repeat the standard geotechnical investigations. (Common tests to re-evaluate the site include the Standard Penetration Test (SPT) for relative density and soil strength, Cone Penetration Test (CPT) for detailed soil profiles, Pressure meter tests (PMT) and Cross-hole/Down-hole Seismic Tests).

In regions where strong earthquakes ($M_W > 7$) may occur, designers are particularly concerned about potential seismic-induced settlements. If the standard tests indicate that the soil is susceptible to settlement under dynamic loading, additional specialized tests may be carried out to better understand and control these effects (Wong et al., 2022; Jurček et al., 2024).

Authors recommend in this situation to perform resonant column or dynamic triaxial tests. Both are showing the variation of the shear modulus (G) and damping (D) with strain (γ) induced in the soil deposit by strong earthquakes ($M_W > 7$). Resonant columns and dynamic triaxial are electro-mechanical devices which could simulate seismic stress/strain to a soil sample from the site of interest, gathered from different depths.

The resonant columns are devices functioning in a dynamical regime to determine soils-specific

parameters and characteristics. They can perform engineering seismology-devoted activities and highlight the non-linear effects of the behaviour of degraded rocks under strong seismic movement and experimental studies on dynamical devices. For example, the non-linear behavior of the soil as observed in laboratory tests on Hardin-Drnevich resonant columns, for strain level exceeding $10^{-5}$ - $10^{-4}$ % is a result of reference in geotechnical research (Bratosin, 2002). The devices use a procedure that analyses the non-linear soil behaviour of shear modulus G = G(γ) and damping function D = D(γ), function of strain level (γ).

Principle of functioning as based on standard configurations, employs a typically cylindrical soil sample fixed at the base and free to vibrate at the top. A torque device attached to the top generates a torsional moment, $M = M_0 \sin\omega t$, and another device generates a longitudinal force $F = F_0 \sin\omega t$ to vibrate the sample, in turn. The Drnevich-type resonant column as in Figure 1 (left), (Bratosin, 2002) typically utilizes only torsional vibration, including refinements to the driving system to better measure damping and accommodate higher strains. Hardin-type device applies $M = M_0 \sin\omega t$ and an axial force (F) to simulate in-situ confining pressure (for example a construction).

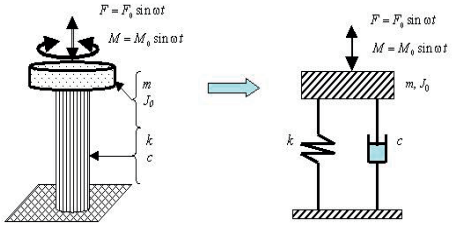



Figure 1. Scheme of resonant column (left) and nonlinear Kelvin-Voigt model (right)

In the Figure 1 (right) (Bratosin et al., 2009) the harmonic excitation for a single degree of freedom model is represented either as external time-varying force $F$ with amplitude $F_0$, or external moment $M$ with excitation amplitude $M_0$. The employed parameters are: moment of inertia of vibration $J_0$, stiffness $k$, damping $c$, pulsation of the external input $\omega$ and mass of the soil sample $m$. The constitutive stress-strain relationships imply the need for viscoelastic laws, and the appropriate model used in this situation is the nonlinear Kelvin-Voigt type (Bratosin et al., 2009).

For higher values of strain (> $10^{-3}$ %), characteristic of strong earthquakes, stress tests are recommended to be performed on a classic/ dynamic triaxial device, (Kumar et al., 2021) which imply a specialized laboratory method used in geotechnical engineering to measure soils behaviour under cyclic or rapidly changing loads, such as those caused by earthquakes.

It is necessary, therefore, the adaptation to the specific situations occurring in the territory, aiming at obtaining the parameters of foundation soil behaviour (Mărmureanu et al., 2004).

The second optional measure employed herein to mitigate the seismic vulnerability of heritage buildings is seismic base-isolation.

Heritage buildings are in general fragile structures, of old materials and in no case designed under seismic codes (also Bucharest situation). During a strong earthquake (for example, above $M_W > 7$) in any construction appear strong shear and axial forces therefore vibrations with higher amplitudes than usual from daily traffic or sporadic construction works. The magnitude of these seismic solicitations that a structure could withstand, and their effects, depend on the characteristics of the construction and the orientation of its main axes with respect to the action of the incoming seismic waves. The purpose of rehabilitation design is to reduce the level of these seismic solicitations and one method to make this happen is to isolate the structure from its foundation through different methods.

The method of seismic base-isolation was already implemented in many parts of the world with very good results in mitigation of seismic vulnerability of important and old buildings (Pietra et al., 2015; Yenidogan & Erdik, 2016; Ghafar et al., 2025). It allows for large horizontal movements while maintaining vertical stiffness, thus minimizing the damage to both structural and non-structural components. Base isolation consists in inserting flexible layer (isolator devices) at the base of the building, separating the structure from its foundations. In the paper is shown that this technique is particularly effective for historic buildings (it reduces the amplitudes in the supra structure), also ensuring operational continuity of the building functioning.

The method was applied also in Bucharest on rehabilitation of four historic buildings. The particularities of these structures are shortly described as follows:

- The Bucharest Town Hall was constructed between 1906 and 1908, using brick masonry combined with reinforced concrete floors supported by turned caissons. A major consolidation project began in 2010, during which a seismic isolation system was installed. The building includes a basement, a ground floor, three upper levels, and an attic.
- The Bucharest University of Economic Studies building on "Calea Griviței" street, constructed between 1905 and 1908, features brick masonry and a truss roof. It includes a basement, a ground floor, two upper levels, and an attic. After consolidation works carried out post 2011, a seismic isolation system was added with two sensors one above and one under it.
- The Triumphal Arch is a distinctive historic monument dating back to the 1930s. Since 2016, when it was rehabilitated, it was monitored using two seismic sensors installed on the isolated structure - one positioned at ground level above the isolator devices and the other at the top of the monument.
- "Foisorul de Foc" constructed between 1890 – 1892, initial a water tank tower, then fire watching from the finish of XIX-th century, then used for other purposes, 42m height.

All four buildings are heritage ones, the first two are still in operation for the initial purpose, administrative and educational, the third is a monument in connection with World War One and the fourth is now the "Museum of Firefighters".

An example of a seismic isolator with rubber and a viscous damper used in retrofitting Bucharest University of Economic Studies building is shown in Figure 2 (Balan et al., 2020).




Figure 2. Example of seismic isolator (left) and viscous damper (right) used for retrofitting

## RESULTS AND DISCUSSIONS

Soil strain thresholds define the transition from linear-elastic behaviour (negligible degradation) to non-linear behaviour (significant degradation). Stiffness degradation typically begins at shear strain levels of 0.0001 % ($10^{-4}$ %) with significant degradation occurring above 0.01 % - 0.1 %. Thresholds are lower for clay (1-2 x $10^{-4}$ %) compared to sand (3-4 x $10^{-4}$ %). For geotechnical applications, understanding these thresholds is critical because strains in the soil, often called the "active compression zone", can lead to permanent settlement or deformation if the threshold is exceeded.

The "active compression zone" refers to the depth within the soil profile where the applied stress (e.g., from a building, embankment, or tunnel) exceeds the soil's strength, causing significant, non-recoverable compression and rearrangement of soil particles.

In engineering, this zone defines the depth over which changes in loading or moisture content will cause substantial settlement or heaving. If foundations are placed above this zone without addressing the compression, long-term settlement will occur.

Exceeding these thresholds leads to different types of settlement: consolidation, consisting in gradual, long-term squeezing of water from saturated soil voids, and creep, which is a long-term, time-dependent settlement that occurs even after excess pore water pressure has dissipated, driven by the distortion of the soil skeleton. Creep in soft clays is a long-term geotechnical phenomenon characterized by time-dependent settlement that persists even after excess pore water pressure from primary consolidation have completely dissipated. This process is driven by the viscous deformation, rearrangement, and inter-particle sliding of the soil skeleton under constant effective stress. In soft, highly compressible soils (e.g., soils like organic clays or soft mud, characterized by high water content, low shear strength, and often a high degree of saturation, including several types of soft, cohesive soils), creep can produce substantial deformation over decades, often leading to settlement that exceeds the magnitude of initial consolidation settlement. The magnitude of creep is heavily influenced by the soil's stress history (over consolidation ratio),

the stress level applied, and the soil's inherent anisotropy.

Clays typically exhibit higher, time-dependent strain (consolidation), while sand strains are more immediate. Rapid loading (dynamic, seismic) can lead to higher strains and liquefaction, whereas slow, drained loading causes smaller, manageable strains. Therefore, in geotechnical engineering, seismic design assumes high-risk conditions requiring soil improvement, while static design often deals with smaller deformation levels.

To mitigate these risks, geotechnical engineers use soil strengthening, preloading, or deep foundation systems to bypass this zone, ensuring that strains remain within the allowable elastic limit (Chang et al., 2016; Dammala & Krishna, 2019).

When a soil deposit experiences a medium range of strain, its behaviour transitions to elasto-plastic, and the shear modulus begins to decrease as the shear strain increases. Based on the resonant column tests developed for this study, this behaviour initiates at a shear strain level of approximately $10^{-5}$ % (see Figure 3). In this regime, the damping ratio serves to quantify the energy absorption capacity of the soil.

Resonant column tests provide a quantitative assessment of these dynamic soil properties across their entire range of definition, making the resulting data highly valuable for calibrating and evaluating nonlinear viscoelastic models under dynamic loading. Ultimately, because the behaviour of soils and rocks is fundamentally dependent on the loading level, this characteristic non-linear response directly influences the dynamic performance of the entire site-structure system.

Data gathered from geological, geotechnical, and hydrogeological boreholes across the city have successfully mapped the sequence of subsoil deposits. By utilizing seismic measurements and geotechnical laboratory analysis on the core samples from these drillings, representative dynamic parameters of the local soils and rocks can be determined (Stokoe et al., 1999).

Structures founded on these superficial layers are highly susceptible to the effects of ground shaking. For instance, loose soils and unconsolidated sediments can significantly amplify ground motion, while water-saturated sediments are prone to soil liquefaction. During an earthquake, these phenomena can lead to a complete loss of ground bearing capacity, ultimately resulting in the catastrophic collapse of overlying buildings.

Results obtained using these optional soil tests are illustrated in Figure 3 (NATO Project, 2005) for several soil samples tested with the Drnevich resonant column device from one site (“Tineretului Park”) in Bucharest. The samples include: sandy clay (4-4.5 m depth), coarse sand (7-8.5 m), fine sand (21-24 m), and gravel (35-37 m). As shown in the graph, the shear modulus G decreases - by as much as 50 % for some materials - while the damping ratio D increases with shear strain ($\gamma$).

Tests performed on dynamic triaxial device, Figure 4, (NATO project, 2005) show that equivalent shear modulus, $G_{eq} = G = E/2(1+ \nu)$ for gravel samples is decreasing while hysteretic damping ratio h (%) is increasing with single amplitude shear strain $\gamma_{sa}$, The equivalent shear modulus is defined as secant shear modulus used to represent the nonlinear stress-strain behaviour of soils under cyclic or dynamic loading (e.g. earthquakes, machine vibrations), and $\gamma_{sa}= (\gamma_{max} - \gamma_{min})/2$ is maximum shear strain reached in one direction (where $\gamma_{max}$, $\gamma_{min}$ are maximum, respectively minimum shear strain). The soil specimens were drilled from the same site located in Bucharest (“Tineretului Park’’) at 35 - 37 m depth.

The results are of relevance for various sectors in geotechnics and with implications in evaluating factors of seismic hazard, the path of propagating the seismic waves, as well as for advancing the fundamental knowledge in understanding the phenomena in soil-structure interaction.

The test devices show the behaviour of soils, the reduction of shear modulus (G) and increase in damping ratio (D) with increasing strain $\gamma$ (as caused by strong earthquakes, with moment magnitude $M_w > 7$, and strain above $10^{-4}$ %). Previous studies concluded that a strain of 3.5 x $10^{-5}$ % may roughly corresponds to a Gutenberg-Richter magnitude of $M_{GR} = 6.1$, while higher level of strain of 1.4 x $10^{-3}$ % corresponds to a magnitude of $M_{GR} = 7.2$ (earthquake of March 4, 1977) (Mărmureanu, 2020). This behavior depends on the soil or rock type (soft degraded, cohesive, coarse-grained or noncohesive,

soft/degraded or hard/stable, etc.), sample depth and other stratigraphy and geological conditions.

Higher magnitude events may induce cyclic shear strains ranging between 0.01 % ($10^{-4}$) and 0.5 % (5 x $10^{-3}$). This would lead to significant pore pressure generation, large deformations, and potential liquefaction.

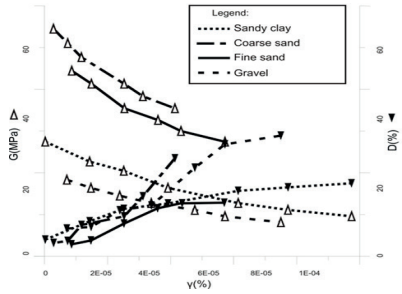



Figure 3. Resonant column tests for core samples (from site "Parcul Tineretului")

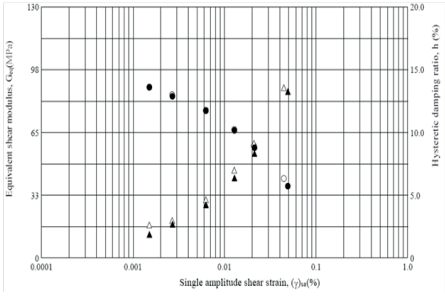



Figure 4: Triaxial tests results for gravel samples (from site "Parcul Tineretului")

High-intensity seismic events triggered by Vrancea intermediate-depth seismic source can produce severe damages and create significant amplification in saturated soils, often leading to large strain, non-linear deformation. The extreme strains values higher than > 1%–10%, may indicate that the soil structure has essentially lost its capacity to bear loads, leading to progressive failure, where the failure zone spreads and induces large, often uncontrollable, deformations in overlying structures.

Based on the provided results, the dynamic model (often in the context of soil-structure interaction or seismic response) assumes a strong dependence of the soil on several, often interlinked factors. For saturated soils, the response is strongly dependent on whether the loading occurs under drained or undrained conditions, which affects pore water pressure and, subsequently, soil stiffness.

In the second part of the study, the goal was to compute the efficiency of seismic isolation for Bucharest University of Economic Studies (ASE, Victor Slavescu) building in Bucharest.

The sensors are placed under and immediately above the seismic isolator, allowing both ground and structure coupling, respectively. They are part of a system consisting of a sensor network and the Data Centre (NDC) capable of acquiring, exchanging and processing data in real time. The computation in terms of maximum recorded accelerations (Amax) and maximum spectral accelerations (SAmax), performed by the Antelope automated system (BRTT, 2018), installed at the National Institute for Earth Physics provides information on the behaviour of the building and the performance of the insulation. The results of monitoring activity and recording of accelerations for 5.5 $M_W$ earthquake of October 28, 2018 (148 km focal depth), (ROMPLUS Catalog, 2025) in this seismic isolated building were analyzed, from the perspective of the earthquake protection system performance. This earthquake was the strongest that hit Bucharest in the last 10 years and originates in the Vrancea intermediate-depth focal area (see Table 1, Balan et al., 2020). All the data above the isolator are consistently less than those under the isolator for both (horizontal) directions N-S and E-W (see Table 1). The maximum values, $A_{max}$, obtained from the recordings above isolator is 3.8 less on N-S direction and 2.12 less on E-W than those under isolator; in the case of spectral response, the maximum spectral acceleration, $SA_{max}$, above the isolator is 3.21 less on N-S direction and 2.1 less on E-W directions than those under isolator.

Table 1. Engineering parameters (maximum recorded acceleration, maximum spectral acceleration) for the 5.5 $M_W$, October 28, 2018 earthquake

| Earthquake ($M_W$ = 5.5) | Acceleration and spectral acceleration ($cm/s^2$) | Position of sensor | |
|---|---|---|---|
| | | Above isolator | Under isolator |
| Component N-S | $A_{max}$ | 33.4 | 129.4 |
| | $SA_{max}$ | 105.0 | 337.2 |
| Component E-W | $A_{max}$ | 46.5 | 98.6 |
| | $SA_{max}$ | 187.6 | 349.9 |

Based on this type of analysis of structural performance during seismic events, the findings confirm that base isolation systems offer a non-invasive, reliable solution for retrofitting older, vulnerable structures, enabling them to withstand earthquakes with minimal damage**.** Base isolation systems decouple the building from the ground, resulting in lower acceleration at upper floor levels compared to fixed-base, non-isolated models. These results support the use of this (modern) technology to rehabilitate infrastructure that was built before modern seismic codes.

For in-depths investigations in this paper were used: resonant column and dynamic triaxial. The two dynamic nonlinear functions modeling the material strength in resonant column experime nts, G = G(γ) and damping D = D(γ) are determined for the soil layers. As a matter a fact almost all site materials exhibit degradable material behavior. However, some of them more and others less, see type of soils in Figure 3.

In soil laboratory testing and geotechnical earthquake engineering, soil cyclic shear strain levels are generally correlated to earthquake magnitude through the intensity of ground shaking (Peak Ground Acceleration, PGA) and the number of loading cycles, which increase with magnitude.

The decrease in the shear modulus (G), could be even 50%, leads to a proportional increase in soil settlements, which can compromise the serviceability and structural integrity of a building.

In geotechnical design, the settlement of a foundation is inversely proportional to the stiffness of the soil. Since G is related to the Young's modulus (E) by the relationship $G = \frac{E}{2(1+\nu)}$, where $\nu$ is Poisson's ratio, a reduction in G directly impacts the elastic modulus used to calculate settlement.

This situation could result in damage in the structure and interior walls. G is a stiffness parameter and its degradation often correlates with a loss in shear strength, potentially reducing the ultimate bearing capacity of the foundation.

In experiments such as cyclic triaxial or resonant column tests, the induced strain levels correspond to varying seismic intensities. often classified by magnitude and proximity to the source. Soil strains generally scale with earthquake magnitude ($M_W$), with significant, non-linear, and permanent deformations (liquefaction or failure) occurring at higher strain levels, typically associated with stronger earthquakes. For moderate to large earthquakes $6 < M_W < 7$ cyclic triaxial or cyclic simple shear tests employed throughout this work show the pore water pressure generation, especially in loose, saturated sands. For large to major magnitudes, $M_W > 7$ high nonlinear behaviour, significant pore pressure generation, and potential for soil liquefaction appear. In many studies, a shear strain of 0.1 % - 0.5 % is considered the threshold for structural damage or significant liquefaction (Díaz-Rodríguez & López-Molina, 2008; Hazirbaba & Omarow, 2019).

Strains exceeding the 0.1 % threshold in soft, saturated soil samples often trigger cyclic softening (degradation, in clays) or liquefaction (in sands), causing a rapid reduction in shear strength and stiffness. The large number of cycles causes a significant pore water pressure level, which reduces the effective stress of the soil, leading to significant post-earthquake cyclic settlement. In soft, saturated alluvial deposits, this mechanism can cause massive ground deformation and substantial settlement.

The paper highlights the significance of knowing the potential of dynamic behaviour of the soil strata under heritage/important buildings during strong seismic events, for taking all measures in the design process to limit such deformations. This way structural damage may be avoided. To have as comprehensive as possible and reliable site information, the necessity is highlighted for considering this method at site evaluation for a safer environment and mitigation of the seismic risk.

By this method, laboratory data are integrated with the parameters available at the site. This approach makes it possible to estimate the site-specific properties by assessing their variability under different loading conditions for the soil components.

Assessing the dynamic parameters for seismic response in Bucharest requires specialized consideration of its unique geological setting, characterized by deep, unconsolidated sedimentary layers and significant intermediate-depth Vrancea earthquakes. A proper estimation of the seismic response involves these

parameters, especially for buildings that are particularly vulnerable to the characteristic long-period, high-intensity shaking experienced in Bucharest. (Bratu & Dobrescu, 2019).
The data processed from recordings on the studied building show an effective earthquake protection system, with a reduction of signal with a factor in the range from 2.0 to 3.8. The output consists in engineering parameters that are maximum acceleration $A_{max}$ recorded on two horizontal directions (N-S, E-W), and the maximum spectral acceleration ($SA_{max}$). The retrofitting technique referenced herein is efficient in urban areas in relation with local and regional seismicity and local site effects parameters (De Domenico et al., 2019).

## CONCLUSIONS

The paper aim is to put forward two optional solutions in the case of rehabilitation of heritage buildings. These buildings are old ones (more than 80-90 years, or even much more) and at their construction there were no building codes with seismic specifications. One of the weak points for these kinds of structures is the foundation soil not studied enough in the design process. The seismic waves are coming from the soil deposit to foundations and structure. In case of rehabilitating such a structure, we should check that the soil would not permit settlements in case of a strong earthquake and this is presented in first case, because a settlement could result in structure damage due to new forces developed in it. If the designers find out that settlements could occur it must be found solutions for consolidating the soil deposit where the construction is situated.
Larger magnitude earthquakes ($M_W$ = 7.2−7.4) create higher PGA and are characterized by longer duration, which generate a higher equivalent number of uniform cycles leading to larger shear strains, with values often exceeding 0.1 % in saturated, soft alluvial soil samples, causing significant cyclic settlement. These conditions lead to strong geotechnical impacts. For example, strains exceeding the 0.1 % threshold in soft, saturated soil samples often trigger "cyclic softening" (in clays) or liquefaction (in sands), causing a rapid reduction in shear strength and stiffness. The large number of cycles causes a significant pore water pressure level, which reduces the effective stress of the soil, leading to significant post-earthquake cyclic settlement. In soft, saturated alluvial deposits, this mechanism can cause massive ground deformation and substantial settlement.
The dynamic tests are used to develop nonlinear constitutive models that define the stress-strain relationship. These models are essential for predicting how soil layers amplify or attenuate ground motion, and how they interact with structures (e.g., in terms of pore-water pressure development and stiffness degradation).
Many old buildings do not have structures to withstand shear and axial forces from strong earthquakes. Therefore, the option of seismic isolation proved highly effective, because separating structure from foundation were achieved ~ 2-3 times smaller accelerations above the isolating system. By diminishing the acceleration recorded, it reduced also the forces applied on the building during a strong seismic movement. Using seismic sensors, vibration data, or similar analysis to continuously monitor structural health, allows for real-time assessment of building stability. Base isolation effectively reduces floor accelerations providing superior protection compared to conventional stiffening and strengthening action. This methodology helps in drawing attention to the seismic benefits for similar, retrofitted buildings.
The implications of these results regarding collapse prevention and enhancing structural resilience are focused on reducing vulnerability through specific, actionable strategies in the seismic risk management for this highly populated zone.
Utilizing quantitative data can target investments where they will generate the highest return in terms of energy savings, operational efficiency, and structural resilience.
Quantifying the efficacy of seismic isolation on historical, or vulnerable buildings in Romania demonstrates a significant reduction in seismic response (acceleration and spectral acceleration) right above the isolation layer, serving as a key indicator for seismic risk and vulnerability mitigation. This technique can be employed as a strategy for seismic risk mitigation, particularly for buildings in Bucharest exposed to Vrancea intermediate-depth earthquake motions.

Seismic isolation, despite high initial financial costs and technical complexities, is a highly effective and beneficial strategy for protecting heritage constructions. This approach is increasingly considered superior to traditional, more invasive strengthening methods (such as adding concrete walls) because it preserves the original materials and architectural integrity. Initial costs for seismic isolation are generally higher than conventional strengthening due to the cost of isolator devices and complex installation. Despite the upfront investment, seismic isolation can offer a better life-cycle cost by minimizing post-earthquake repair expenses, reducing business interruption.

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