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A DATA-DRIVEN ANALYSIS OF SEISMIC RESPONSE AND STRUCTURAL PERFORMANCE

Daniela DOBRE[1, 3], Iolanda-Gabriela CRAIFALEANU[1, 3], Claudiu-Sorin DRAGOMIR[2, 3], Emil-Sever GEORGESCU[3], Cornelia-Florentina DOBRESCU[3, 4]

[1]Technical University of Civil Engineering Bucharest, 122-124 Lacul Tei Blvd, 020396, District 2, Bucharest, Romania
[2]University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Mărăști Blvd, 011464, District 1, Bucharest, Romania
[3]NIRD URBAN-INCERC, 266 Pantelimon Road, District 2, Bucharest, Romania
[4]"Dunărea de Jos" University of Galați, 47 Domnească Street, Galați, Romania

Corresponding author email: dobred@hotmail.com

Abstract

Data obtained from seismic instrumentation campaigns enable the identification of buildings' dynamic characteristics, the objective evaluation of structural performance, and the investigation of damage and degradation mechanisms induced by earthquake loading. For each monitored building, detailed information is compiled, including location (city or municipality), year of construction, applicable seismic design code, structural system characteristics, type of functionality (research institutes, administrative, education, healthcare, residential, commercial), site and soil conditions (where available), and the seismic events recorded during its service life. Using simplified dynamic models with natural periods of vibration matching those of instrumented buildings, this paper analyses their structural response to the 1977, 1986, and 1990 Vrancea earthquakes through time-history, linear, and elasto-plastic comparative approaches, and evaluates their seismic performance. Relevant regulatory provisions and findings from previous studies are considered to establish correlations between the exceedance of admissible inter-storey drift limits and observed damage levels. The results demonstrate that long-term seismic instrumentation campaigns are integral to structural health monitoring, providing a robust basis for post-earthquake assessment and risk-informed decision-making.

Key words*: measured response, performance evaluation, structural behaviour.*

INTRODUCTION

Traditional methods for assessing structural performance provide a physical understanding of structural behavior, but they rely on idealized assumptions and uncertain parameters. The development of structural monitoring systems and seismic instrumentation networks, together with advances in computational power and machine learning techniques, has enabled the emergence of data-driven approaches. These approaches use large volumes of empirical data derived from seismic recordings and structural response to identify relationships between excitation and response, detect changes in structural properties, and improve predictive models. At present, data-driven approaches do not replace physics-based models, but rather complement and calibrate them, contributing to the development of modern hybrid frameworks for the analysis and monitoring of structural behavior under seismic actions. Also, data-driven methodologies are particularly useful for analysing soil-structure interaction (SSI) because they rely on measured structural responses rather than assumed soil and foundation parameters. By comparing recordings from the free-field, basement, and upper structural levels, amplification factors can be derived that implicitly capture SSI effects (Dobre & Dragomir, 2018; Dobre et al., 2024). This empirical approach also provides direct insight into how seismic waves are modified by the soil–foundation–structure system and transmitted through the building.

On the other hand, there is a direct connection between the data-driven approach, Building Information Modeling, and Structural Health Monitoring in the management and monitoring of built infrastructure. Consequently, the integration of BIM and SHM within a data-driven framework enables more efficient

structural monitoring, supports predictive maintenance, and contributes to the development of digital twins for infrastructure systems (Dobre et al., 2025).

The importance of pre-earthquake SHM data was proved after the 1977 earthquake (Balan et al., 1982), when INCERC published measured vibration periods for 47 buildings, before and after the earthquake, with obvious increases due to damage, thus a comparison was possible for both that situation and for the one after strengthening, if done. The unique INCERC accelerogram of the March 4, 1977, Vrancea earthquake (Mw 7.4) revealed a pronounced long-period spectral content, which contributed to damage in tall and slender structures. However, relying on a single seismic record limits the generalization of structural response characteristics. In contrast, the available database includes multiple Vrancea earthquakes with different spectral features, complemented by ambient vibration recordings obtained from structural health monitoring. This expanded dataset enables a data-driven analysis framework, where structural behavior is inferred from a larger set of measured responses, allowing for more robust identification of dynamic properties and a better understanding of variability in soil–structure interaction effects (Pavel et al., 2018; 2020; Del Gaudio et al., 2019; Morandi & Albanesi, 2026). Conceptual differences between the two approaches are presented in Table 1.

Table 1. Fundamental differences between physics-based and data-driven frameworks

Traditional Approach	Data-Driven Approach
Physics-based (constitutive material models, structural dynamics equations, idealized boundary conditions)	Data-based (acceleration time histories, drift measurements, frequency shifts, damping evolution)
Assumed parameters (elastic modulus, damping ratio (often 5%), boundary fixity, soil-structure interaction, hinge properties)	Measured parameters (actual natural frequencies, actual damping ratios, real stiffness degradation, residual displacements)
Pre-event prediction (predicts performance before earthquake occurs, uses design spectra, checks demand vs capacity)	Real-time/post-event learning (seismic response recordings evaluated immediately after each event, models recalibrated accordingly)
Static model (analytical model created at the design stage, remains unchanged, assumes constant structural properties)	Continuously updated model (modal properties tracked over time, damage detected via frequency drift, stiffness degradation quantified)
Physics-informed models: integration of physical model data with instrumentation data	

The workflow illustrated in Figure 1 represents the internal process of the data-driven analysis stage.

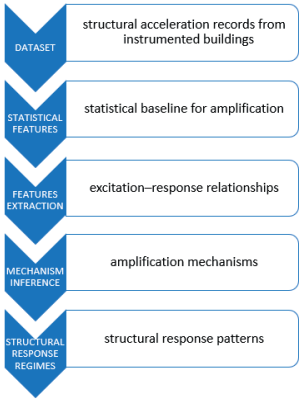


Figure 1. Data-driven workflow

Starting from structural acceleration records obtained from instrumented buildings, statistical characterization and feature extraction are used to identify excitation–response relationships, infer amplification mechanisms, and classify structural response regimes. These insights contribute to the development and calibration of hybrid physics-based and data-driven models used in structural health monitoring and digital twin frameworks.

MATERIALS AND METHODS

The methodological framework adopted in this study combines physics-based structural modeling with empirical evidence derived from seismic monitoring data.

In the first direction, a set of buildings is idealized as simplified dynamic systems represented by single-degree-of-freedom models with identical fundamental vibration periods (Saiidi & Sozen, 1979; 1981), while differing in key structural characteristics such as height, number of stories, and construction period. The seismic input consists of recorded accelerograms corresponding to the Vrancea earthquakes of 1977, 1986, and 1990, which are used as input motions in time-history analyses. Both elastic and inelastic responses are evaluated, accounting for stiffness degradation; however, the fundamental vibration period is assumed to remain approximately constant, as

the expected stiffness reduction is relatively small. Structural response is characterized through parameters such as inter-storey drift ratios, which are compared with code-based thresholds associated with different damage states (P100-1/2013; Luca et al., 2015; Zaker Esteghamati at al., 2018; Ibrahim & Makhloof, 2023; Habibi & Asadi, 2017; Sen et al., 2023; Mohsenian et al., 2024; Genikomsou et al., 2025).

The second direction, shown in Figure 1, supports the numerical investigation by analysing recorded data from a case-study of a building equipped with seismic instrumentation. This approach enables the evaluation of seismic motion transfer and amplification throughout the structural system. The amplification factor at the basement level, AF_basement, is defined as the ratio between the acceleration recorded at the basement and the free-field acceleration, expressing how much the seismic motion is amplified from the ground unaffected by the structure to the foundation level. Similarly, the amplification factor at the terrace level, AF_terrace, describes the amplification of motion from the free field to the top of the building. Finally, the structural amplification factor, T, represents the ratio between the terrace and basement amplification, indicating how much the motion increases vertically from the foundation to the top of the structure.

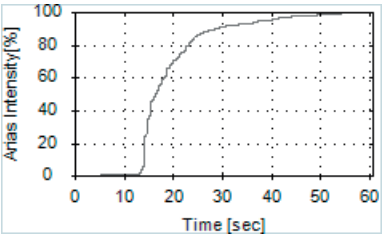
Together, these two directions provide complementary perspectives on structural behavior under seismic excitation: numerical simulations allow the systematic investigation of structural performance across different building configurations, while the instrumentation-based analysis provides empirical evidence of amplification mechanisms and response patterns observed in real structures.

Seismic monitoring systems provide acceleration data from instrumented buildings under ambient vibrations and earthquake events, forming the empirical basis for data-driven analysis. The recorded signals are pre-processed to remove trends and noise and are subsequently analysed using system identification techniques to extract modal parameters such as natural frequencies, damping ratios, and mode shapes. Additional statistical and spectral features are computed and organized into a structured feature matrix describing the dynamic characteristics of the monitored structure.

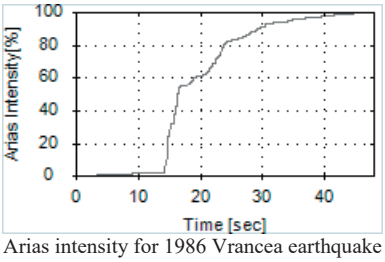
RESULTS AND DISCUSSIONS

The first approach focuses on the seismic response of the structural models. The results obtained for the different structural models constitute a dataset that will subsequently allow for additional comparative analyses aimed at identifying trends and correlations between the structural parameters of buildings (height, number of storeys, fundamental vibration period, year of construction) and seismic response indicators (inter-storey displacements – angular drifts, stiffness degradation). By applying statistical analysis methods to these basic results, the objective is to highlight the distribution of the structural response and to estimate the probability of exceeding certain performance thresholds associated with different damage levels, as defined in current codes or existing studies. Thus,

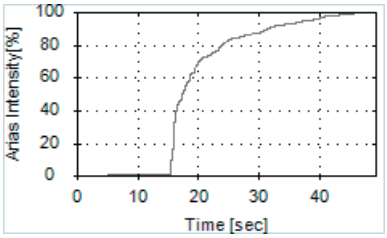
– The maximum spectral seismic response, linear and bilinear, associated with different dynamic characteristics, is estimated.
– Based on the determined dynamic characteristics, the structural behavior under the three types of seismic actions (Vrancea 1977, 1986, 1990, with the total energy of the seismic ground motion over time, represented by the Arias intensity) is highlighted, as shown in Figure 2a and Figure 2b.



Arias intensity for 1977 Vrancea earthquake



Arias intensity for 1986 Vrancea earthquake



Arias intensity for 1990 Vrancea earthquake

Figure 2a. Arias Intensity and Cumulative Severity

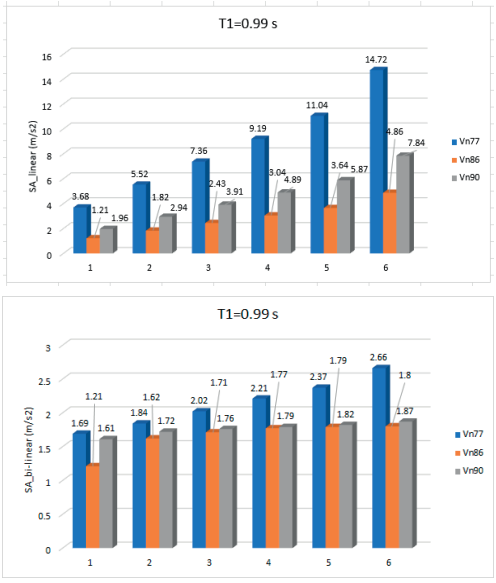


Figure 2b. Spectral acceleration in the linear and bilinear domain

– Two correlations are identified between the period and height (Figure 3a), and between the period and the spectral displacement (Figure 3b).

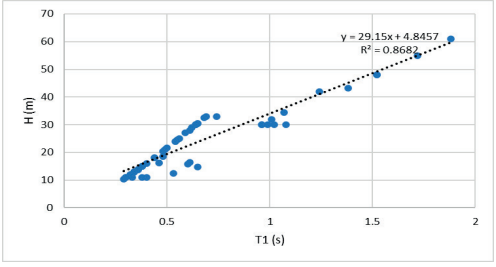


Figure 3a. Period and Height relationship

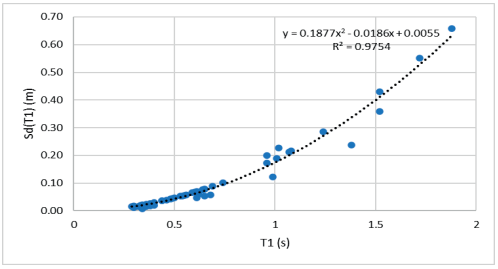


Figure 3b. Period and Spectral displacement relationship

– For structural systems with different dynamic characteristics, the results of a time-history analysis, both linear and nonlinear (comparative), are presented, considering the inter-storey displacement response under the Vrancea 1977, 1986, and 1990 seismic actions (Figure 4).

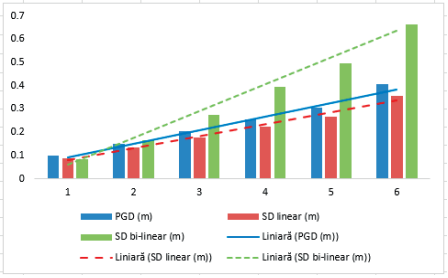
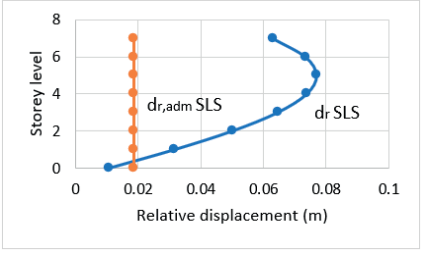


Figure 4. Structural displacement response (T_1 = 0.99 s)

– For several of the absolute storey displacements mentioned above, determined by considering a linear variation along the height of the model and multiplied by a shape function, the relative displacements are calculated for the Serviceability Limit State (SLS) and the Ultimate Limit State (ULS), as well as the inter-storey drifts (angular drifts) and their allowable limits (Figure 5).



Inter-storey drifts - allowable limits (linear)

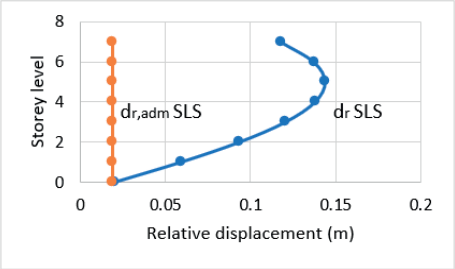


Figure 5. Seismic performance of the structural system with T_1 = 0.99 s (linear and bilinear analysis at SLS)

– Identification of situations in which, both in the linear and nonlinear domains, residual displacements occur - an indicator of structural performance.
– Estimation of the possible damage level through the relationship between the accelerogram scaling factor and the drift/drift indicator.

The variation of inter-storey drift along the height of the building is illustrated in Figure 6a for linear analysis and in Figure 6b for bilinear analysis.

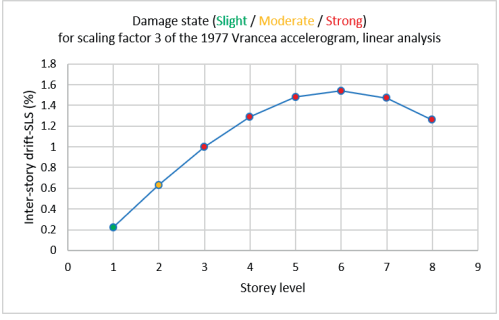


Figure 6a. Distribution of inter-storey drift along the building height and corresponding damage state for Scaling Factor = 3 (Vrancea 1977), linear analysis

For the linear analysis, drift values increase with the increase of the accelerogram scaling factor. For scaling factor 3, the SLS drift ranges between 0.22% and 1.54%, while the SLU drift varies between 0.84% and 5.95%, with predominantly serious damage at the upper floors. In the bilinear analysis, drift values are significantly higher. For scaling factor 3, the maximum values reach 2.87% (SLS) and 11.08% (SLU), indicating severe damage at the upper floors.

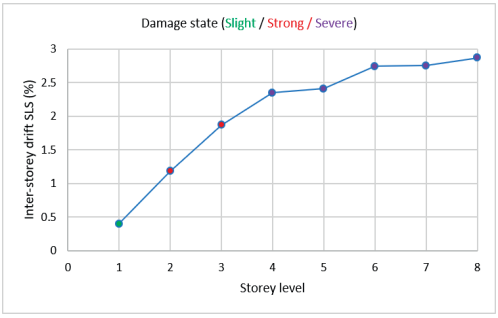


Figure 6b. Distribution of inter-storey drift along the building height and corresponding damage state for Scaling Factor = 3 (Vrancea 1977), bilinear analysis

The second approach uses the obtained results to perform a statistical characterization of the amplification indicators, highlighting their distribution and variability. Descriptive statistics were calculated for the indicators AF_basement ($A_{basement}/A_{free-field}$), AF_teracce ($A_{terrace}/A_{free-field}$), and T ($A_{terrace}/A_{basement}$) to characterize the baselines for 2024 and 2025 in both NS and EV categories. The statistical analysis included the computation of minimum and maximum values, medians, and quartiles (Q1–Q3, corresponding to the 25th, 50th, and 75th percentiles) in order to describe the distribution of the data and assess their variability. Based on these indicators, characteristic ratios were derived, allowing the identification of the amplification patterns expressed through the relationships between the considered variables. The obtained values provide an overview of the variability of the ratios and enable a comparative assessment of the two baselines.

To enhance the visual comparison of indicator distributions, the statistical results were illustrated graphically, enabling a direct comparison between the baselines corresponding to 2024 and 2025, for the NS and EW categories. Figure 7 illustrates the quartile distribution of the amplification factors for the 2024 and 2025 baselines, showing a progressive increase in amplification from Q1 to P95-including the 95th percentile. The results indicate slightly higher basement amplification for the 2025 baseline compared to 2024, Figure 7a, while the terrace amplification exhibits a stronger increase toward the upper quartiles, Figure 7b.

The ratio T highlights the vertical amplification between the basement and terrace levels, with higher values observed for the upper quartiles, Figure 7c. These observations reveal a consistent and repeatable response pattern, characterized by a monotonic increase in amplification across quartiles and a clear amplification gradient from the basement to the terrace level.

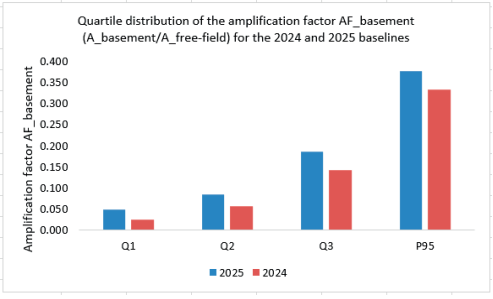


Figure 7a. Amplification trends between the 2024 and 2025 baselines for AF_basement

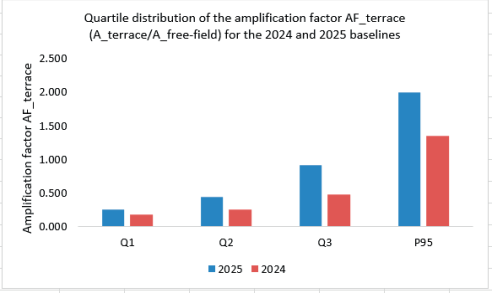


Figure 7b. Amplification trends between the 2024 and 2025 baselines for AF_terrace

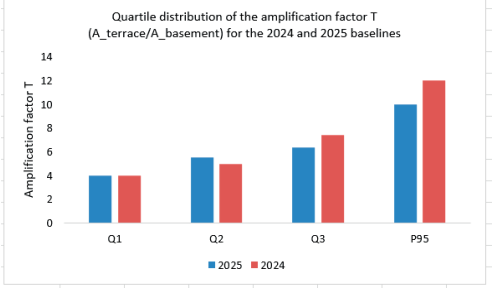


Figure 7c. Amplification trends between the 2024 and 2025 baselines for T

While the basement amplification remains relatively similar for both components, the terrace amplification shows significantly higher values in the EW direction, particularly toward the upper percentile range. This behavior suggests a stronger structural response along the EW axis. The median values indicate a consistent increase in amplification with height, reflecting the typical structural response, while the higher mean values suggest the presence of occasional higher-amplitude events. Tracking the temporal evolution of median values and interquartile ranges enables the identification of changes in both the central tendency and variability of the structural response. Stable quartile distributions over time indicate consistent behavior, whereas systematic shifts in median or dispersion may reflect changes in structural properties or soil–structure interaction conditions. Together, the two approaches provide complementary perspectives, combining the evaluation of structural response with the statistical interpretation of the resulting indicators.

CONCLUSIONS

Data-driven approaches offer several important advantages in structural monitoring and seismic performance assessment. Unlike traditional analytical models, which rely on assumed parameters such as damping ratios, stiffness degradation, or boundary conditions, data-driven methods use measured structural responses. Dynamic characteristics - including natural frequencies, damping ratios, and modal shapes - are extracted directly from recorded time histories, reflecting the actual behavior of the structure.

Another key advantage is the possibility of post-event evaluation and model calibration. Structural properties may change over time due to cracking, ageing, damage, or retrofitting. Monitoring data enables the detection of frequency shifts, changes in damping, or residual displacements, providing insight into the current structural condition and improving reliability assessment throughout the life-cycle of the building.

Data-driven approaches also support probabilistic performance evaluation by leveraging large sets of recorded structural responses. By processing multiple seismic and ambient vibration records, response parameters

such as peak floor acceleration or inter-storey drift are extracted and statistically analysed. Empirical distributions are then constructed using descriptive statistics (e.g., median, quartiles) or fitted probability models, allowing the variability and uncertainty of the structural response to be quantified. This approach reduces reliance on purely theoretical assumptions and provides a more realistic representation of structural behavior based on measured data.

Additionally, aggregated monitoring databases enable comparative analysis of reinforced concrete and steel structures from various perspectives (Stoian et al., 2022; Köber et al., 2024a,b), enabling the identification of performance trends under similar demands. Such comparisons can support improvements in design provisions and retrofit strategies.

Despite these advantages, several limitations must be considered. The availability of high-quality monitoring data remains limited, particularly for extreme seismic events, which are rarely recorded in real structures. Data quality may also be affected by noise, sensor drift, or incomplete records, requiring careful validation and pre-processing. Machine learning techniques can approximate nonlinear seismic response much faster than conventional dynamic analyses, making them useful for evaluating a large number of structures. However, the performance of the models depends on the quality of the data, the choice of input parameters, and the ability of the model to generalize to new seismic motions or structural typologies (Noor, 2025).

Another challenge is generalization. Structural response depends on building geometry, material properties, and soil conditions, meaning that observations from one structure cannot always be transferred to others. Moreover, data-driven approaches primarily identify statistical correlations rather than physical mechanisms, which limits their ability to explain processes such as stiffness degradation or damage localization.

For these reasons, data-driven methodologies are best used in combination with physics-based models. Analytical approaches provide the mechanical framework governing structural behavior, while empirical data improve calibration, validation, and uncertainty assessment.

Integrating data-driven methods with consistent analytical models creates a strong framework for understanding and enhancing structural resilience.

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