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THE EVOLUTION OF THE DYNAMIC CHARACTERISTICS OF THE SOIL-STRUCTURE SYSTEM IN CASE OF A UNIVERSITY BUILDING SEISMIC MONITORING

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Abstract

In Romania, there are several legislative guidelines regarding the activity of seismic instrumentation/monitoring, which can support this activity in a coherent and effective way (Seismic Design Code, P 100-1/2013, Annex A). The monitoring of the Faculty of Biotechnology building is carried out using 3 Granite triaxial sensors, arranged one each on the top, in the basement and in the free-field. For each of the recordings, the Fourier spectrum, also response and power spectrum, can be represented, using different options related to axes, corrections etc. The processing of the records leads to the determination of the instantaneous maximum values of the accelerations, velocities, displacements. A comparative analysis over time will be presented for the level of vibrations recorded and for the frequency range obtained in free-field, basement, top conditions, as well as an analysis of vibrations from an ambient comfort point of view. Beyond the legislative aspects, this activity responds to the need to know both the characteristics of earthquakes and the structural characteristics of the building.

Key words*: ambient comfort, frequencies, vibrations.*

INTRODUCTION

In Romania, there are several legislative guidelines regarding the activity of seismic instrumentation/monitoring, which can support it in a coherent and effective way (Seismic Design Code, P 100-1/2013, Annex A, and the Regulation on the management of emergency situations generated by the earthquake, from 2023). Within this complex research activity, the existing concept regarding the location of the sensors for vibration measurement, inside the structural system, but also outside, offers the possibility of obtaining more information about the general structural behaviour (Lungu et al., 2004; Tiganescu et al., 2022).

The vulnerability on the one hand and seismic performance of buildings on the other hand are estimated most of the time considering their structural systems embedded at the base, in which case the sensor located outside the building is not of particular interest, but the studies developed over time try to quantify the effects of the phenomenon of soil-structure interaction (with its kinematic and inertial components), thus requiring the existence of at least one sensor outside, Figure 1.

The effect of the interaction can be an attenuation (dissipation of part of the energy through hysteretic damping, radiation of seismic waves) or an amplification of the dynamic response of the structure (modification of the natural vibration periods of the structural model, longer periods) (Project EUCONS/PN 03 15 02 01, 2004; Project ECOSMARTCONS, 2022). Internationally, there are many provisions regarding the soil-structure interaction included in several important seismic design standards, such as NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures 2001, ATC-40: Seismic Evaluation and Retrofit of Concrete Buildings 1996 and A Practical Guide to Soil-Structure Interaction (The Federal Emergency Management Agency, 2020).

Figure 1. Seismic/ambient vibration monitoring layouts (Celebi, 2000, 2002)

MATERIALS AND METHODS

The defining elements of the soil-structure interaction analysis methods with supporting data from the activity of instrumentation/ monitoring (including vibrations data from the near field, or free-field) are:

- the degree of association of interaction components (kinematic, inertial) and the weight of each in the behaviour of the structural system;
- calculation of transfer functions;
- determination of the translational/rotational motion of the foundation;
- estimation of the influence of soil conditions (location effect, vs. structure-soil interaction);
- determination of impedance functions;
- identification of the system from the input-output relationship, or just from output.

Below are presented some methodological concepts for determining the dynamic structural characteristics from the processing of micro vibration recordings and/or moderate/severe earthquake recordings, with/without the effect of the interaction between the structure and the soil, Figure 2-4, given the following:

- in the case of kinematic interaction, in general, a reduction of the motion at the foundation level is expected in relation to that recorded in the free-field;
- the recorded motion at the foundation level can be evaluated taking into account the superposition of the effects of the two components of the interaction (effective motion);
- the effects of the soil-structure interaction can be increase in the bending and torsional moments in the columns and walls on the ground floor (deformation of the building infrastructure, resulting relative rotations at the base of the columns on the ground floor, amplified even more in the case of non-synchronous motions of the foundation soil).

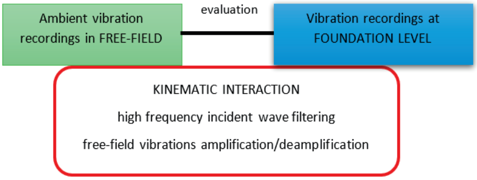

Figure 2. Soil-structure interaction effect: modification of free-field motion characteristics

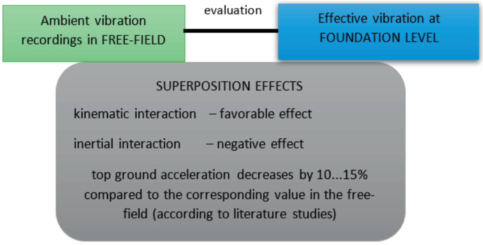

Figure 3. Soil- structure interaction effect: superposition effects

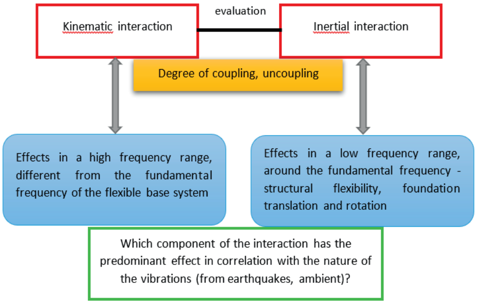

Figure 4. Soil- structure interaction effect: degree of association of interaction components and the weight of each in the behaviour of the structural system

Seismic and vibration monitoring, support tool for soil-structure interaction

The monitoring of the Faculty of Biotechnology building is carried out using 3 Granite triaxial sensors, arranged one each on the top, in the basement and in the free-field (for instance, N-S direction: channel 2 – building exterior; channel 6 – building basement; channel 10 – building top floor), Figure 5. For each of the recordings, the Fourier spectrum, also response and power spectrum, can be represented, using different options related to axes, corrections etc. (Dobre & Dragomir, 2017; Dragomir et al., 2020; Dragomir & Dobre, 2019). The identification of structural dynamic characteristics from ambient vibration measurements as well as according to the simplified formula from P100-1/2023 led to $T_1 = 0.18$ s, according to the seismic zoning map PGA 0.3 g and Tc = 1.6 s.

Figure 5. The building of the Faculty of Biotechnologies. Year of construction 2016, S+P+2E, reinforced concrete structural frames and walls, Granite instrument type

From a morphological point of view and geotechnical investigations for the type of soil, layers, stiffnesses, density, damping, the soil's shear wave velocity (Dobrescu & Călărașu, 2015; 2016), the area is located on the Colentina Plain, with an anthropogenically modified relief, flat and stable, with no risk potential regarding flooding phenomena. From a geological point of view, deposits belonging to the Upper Pleistocene, the high level, appear in the area. In order to establish the foundation conditions on the site, a program was developed regarding the analysis of the foundation soil, which included:

- field surveys, with circular boreholes executed on the site with a depth of up to approx. -6.00 m;
- determining the values of the physical characteristics of the samples collected from the borehole (soil granularity; soil moisture; plasticity limits characterized by the plasticity index and the consistency index).

The results of the laboratory tests carried out on the soil samples collected from the boreholes showed the existence of a fill layer with a variable thickness between 0.50-2.50 m, followed by cohesive soils composed of porous clay, with medium plasticity, weakly cohesive soils - dust clay and non-cohesive soils - sand and sand with gravel, starting with a depth of about -3.50 m.

The stratigraphic columns intercepted following the execution of drilling on the investigated site are highlighted by the sequence of soil layers in the lithological profiles of the drilling as follows: 0.00-0.80 m fill from buried soil and gravel; 0.80-1.20 m dusty clay, dark brown, silty plastic; 1.20-2.20 m clay dust, dark brown, hard; 2.20-2.50 m sandy clayey dust, brown, with finely dispersed carbonates, hard; 2.50-3.50 m sandy dust, yellowish, cloudy plastic; 3.50-3.70 m large sand with rare gravel, yellowish, medium density, wet; 3.70-6.00 m sand with wet yellow gravel (data from a first drilling).

Interaction analysis can be made through experimental approaches (field tests), so in order to identify the phenomenon of soil-structure interaction, an analysis of the recordings from two earthquakes in 2021 and of the ambient vibration measurements from the same year was carried out, Figure 6 and Figure 7, later recordings also from 2018-2022 were analysed.

The effects are expressed by the difference between the free-field motion, from the basement of the building and the response of the building structure at the top level (assuming that the motion of its base is/is not the same as the free-field motion). This difference depends both on the characteristics of the ground motion in the free-field and on the properties of the structure and the foundation environment.

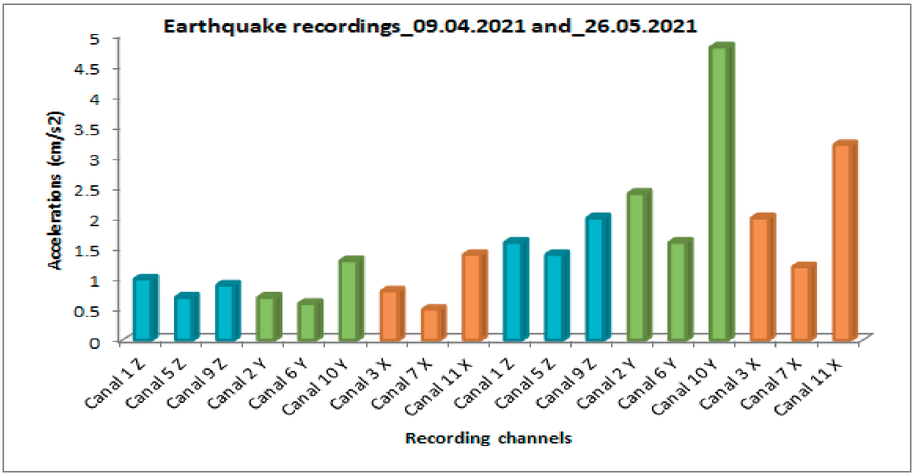

Figure 6. Interaction analysis: seismic acceleration propagation from the free-field to the top level of the building (earthquakes 2021)

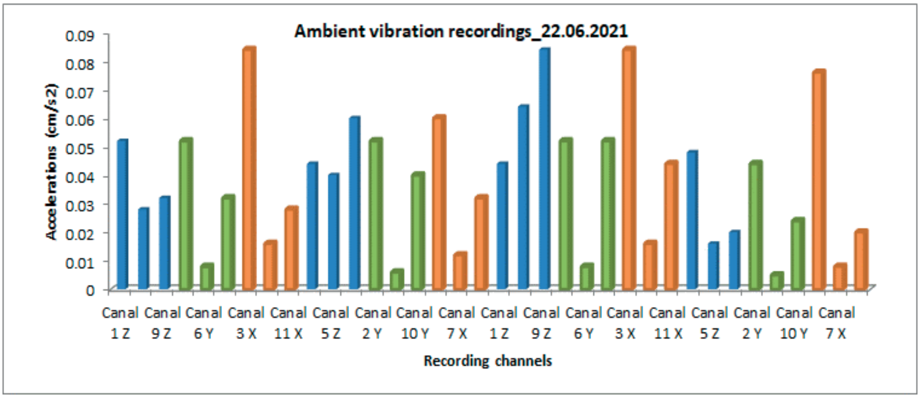

Figure 7. Interaction analysis, ambient acceleration propagation from the free-field to basement and to the top level of the building (2021)

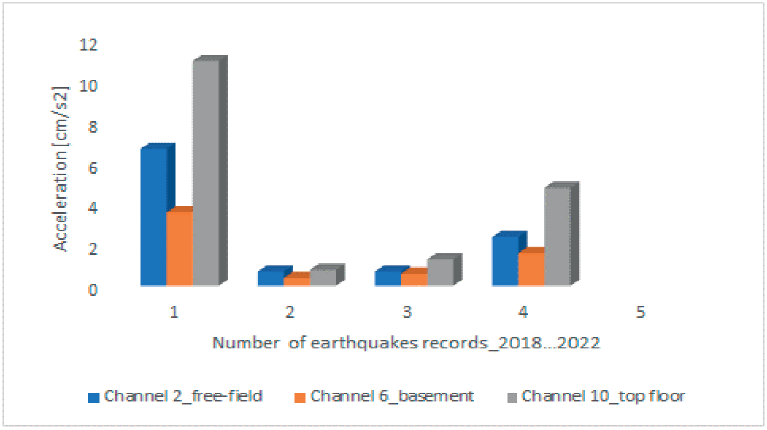

Figure 8. Interaction analysis, seismic acceleration propagation from the free-field to the top level of the building (earthquakes 2018-2022)

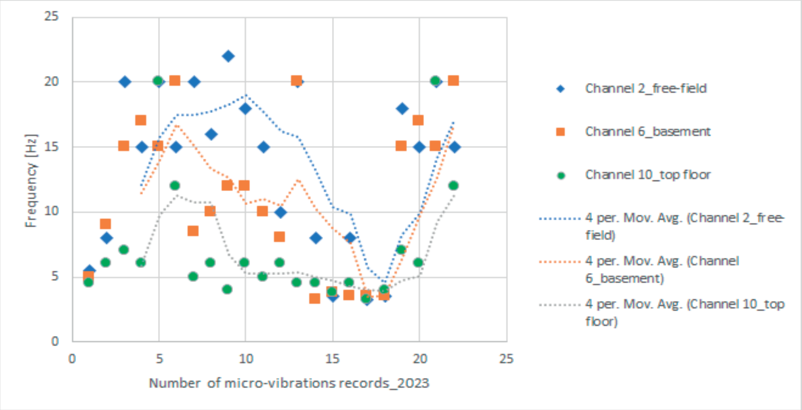

Figure 9. The evolution of the frequency values from the free-field, towards the basement of the building and then vertically towards the top floor

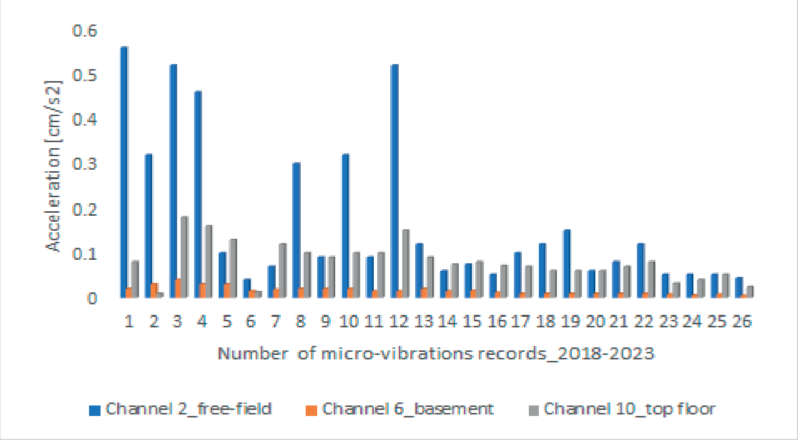

Figure 10. Interaction analysis, ambient acceleration propagation from the free-field to the top level of the building (2018-2022)

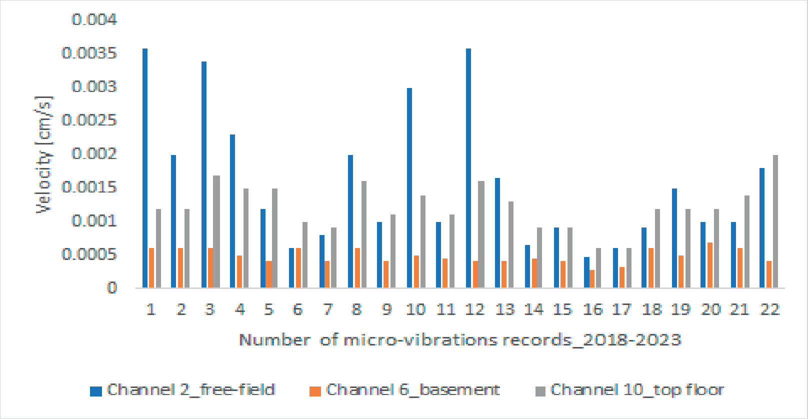

Figure 11. Interaction analysis, ambient velocity propagation from the free field to the top level of the building (2018-2022)

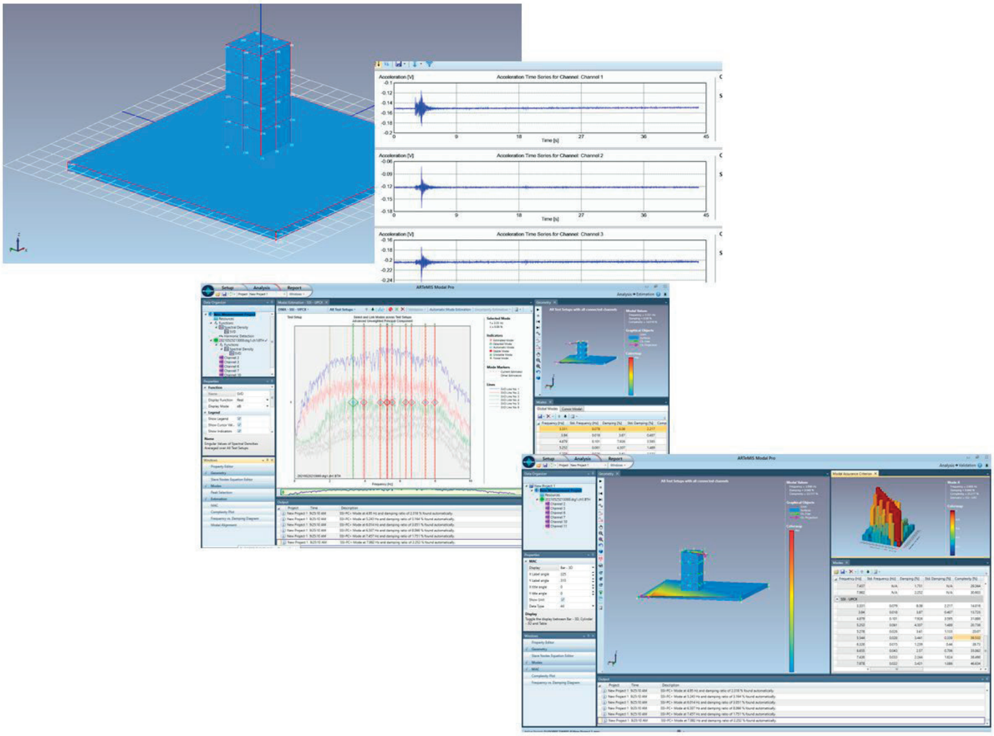

Figure 12. Brief stages of the OMA for the soil-structure assembly (simplified model for the discussed assembly)

The variation of frequencies in relation to 3 measurement points – free-field, basement and top floor, resulting from the ambient micro-vibrations/micro-seismicity recordings (2023) is shown in Figure 8 and Figure 9. The way of propagation of waves and vibrations through the soil conditions specified above highlights the kinematic component of the soil-structure interaction that arises from the presence of the building embedded in the soil (in fact, a disturbance of the free-field vibration due to the presence of structural elements with a stiffness different from that of the soil, at the interface level) and the mechanism differs vertically from the basement to the last level, with an additional displacement at interface caused by the force induced by the motion of the structure (inertial component). Representations for accelerations and velocities are in Figures 10 and 11. Combination of two materials with distinct characteristics and behaviour, the soil and the structure, requires another approach.

Using the records obtained over time, the output-only modal analysis in order to get the dynamic characteristics of the S+P+2E soil-structure assembly is another type of possible analysis, mainly assuming (Figure 12):

- defining the geometry of the structural system;
- entering the file with the data obtained from ambient recordings specifying the sampling interval, specifying the positions and orientations of the sensors on the structure, specifying some parameters for processing the recordings (detrending, decimation, filtering, estimating the spectral density, detecting harmonic oscillations, iteration in the stochastic subspace;
- the calculation of the power spectral density and the estimation and validation of the natural modes of vibration.

RESULTS AND DISCUSSIONS

The processing of the records leads to the determination of the instantaneous maximum values of the accelerations, velocities, displacements. A comparative analysis was presented for the level of vibrations recorded and for the frequency range obtained in free-field, basement, top level.

In order to establish a functional model for the study of the soil-structure interaction, based on the processing of the recordings of small earthquakes and ambient vibrations, the time histories recorded in the free-field, at the basement of the building and at the level of the terrace, were compared. In particular, there is a different situation in the case of recorded earthquakes, compared to the one for recorded ambient vibrations:

- in Figure 6 representation of the acceleration recorded on the channel corresponding to the sensor located in free-field decreases on the channel in the basement and then increases (sometimes accentuated) on the channel associated with the sensor on the building terrace; the same trend is observed in the case of both earthquakes;
- in representation Figure 7 is not observed the same variation of accelerations as in the case of ambient vibration recordings; in most situations, the accelerations in free-field are higher than those at the terrace level, showing that there is no amplification of the motion in the building.

Also, the dominant frequencies in the free-field are sometimes comparable to the corresponding ones at the basement level, which does not unequivocally show a filtering effect induced by the building, encountered in other cases. The differences between the motions in the free-field and those in the basement of the building can indicate the existence of soil-structure effects (kinematic interaction component). The range of frequencies in the free-field in this studied case is either between 10 Hz and 20 Hz, or between 40 Hz and 80 Hz (with multiple peaks), in both directions, x and y.

The amplitude spectra and Fourier transforms of the accelerograms of the recordings were determined, and the dynamic characteristics of the soil-structure system were determined. Thus, according to the processing of the two recordings from the earthquakes, at the level of the terrace, the predominant frequencies are included in the following domains: f_{1x}= 4-5 Hz, f_{1y}= 4-6 Hz. From ambient vibrations, the predominant frequency values are the same, varying only the f_2 and f_3 frequencies.

The inertial interaction component will be properly highlighted after recordings of moderate or severe earthquakes, the modification of the spectral parameters not being important from recordings of dynamic actions of reduced amplitude.

On the other hand, roughly determined by OMA, the natural period of vibration of the soil-structure assembly is T_1 = 0.33 s, and the damping coefficient 9.68% (the main unweighted component).

CONCLUSIONS

Beyond the legislative aspects, this activity responds to the need to know both the characteristics of earthquakes and the structural characteristics of the building.

The importance of the soil-structure interaction phenomenon has been a debated topic for a very long time, showing that it cannot be neglected, but understood in a dynamic context and correlated with a series of aspects regarding the spectral content of the seismic motion and the geotechnical and geological characteristics of a site. On the other hand, in the absence of data from larger earthquakes, micro-vibration/ambient vibration recordings offer an important alternative for structural dynamic analysis and global vulnerability assessment.

The recordings of significant seismic motions, or significant ambient vibrations, obtained both in the free-field (near/far), as well as on the lower, intermediate, or top floor of some buildings, with the possibility of also obtaining other data from the records in their adjacent area, they constitute a valuable source of information for investigating the effect of soil-structure interaction. This investigation also takes into account the type of foundation and soil that properly influence the structural response. The two components of the interaction have a quantified favourable or unfavourable role, once they have been decoupled and properly understood. In principle, the kinematic interaction induces the advantage of reducing the level of motion at the level of the foundation, compared to that in the free-field, but the methods applicable in the studies assume the determination of transfer functions sensitive to the calculations they assume. Regarding the inertial interaction, this involves the preliminary determination of the translation and rotation motion at the foundation level (coupled/decoupled; shear force and moment that induce displacements of the foundation relative to the ground), then the evaluation of the effect on the fundamental period of vibration and the depreciation coefficient. However, neglecting the effects of soil-structure interaction is another approach accepted in many seismic design codes, in countries with high seismicity, as a conservative simplification. More than that, on a more general scale, some results of the monitoring as new findings are transferable and of special technical and legal importance, the elaborated documents representing the basis for the Technical Book of Building, and the archived information constituting initial records for the future data obtained after a major earthquake. Finding a reliable solution for a quick analysis after an earthquake, by generating a report with the dynamic parameters of the monitored buildings behaviour, is a challenge of a strategic and logistical nature, of acquisition, storage and continuous processing of data, elaboration of analytical models for validation, in context of digital approach for structural engineering.

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