SPECIAL ISSUES BETWEEN ADJACENT BUILDINGS WITH DIFFERENT HEIGHTS AND THE PECULIAR VRANCEA EARTHQUAKES

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Abstract

The earthquake risk in Romania is one of the highest in Europe and the seismic hazard for almost half of the country, including its capital, is determined by the Vrancea seismic region. The strongest Vrancea earthquake ever known is generally accepted to be the October 26, 1802 seismic event ($M_{G\text{-}R} = 7.5$). The Vrancea earthquake with the highest seismic magnitude in the 20th century was the November 10, 1940 seismic event ($M_{G\text{-}R} = 7.4$). The most destructive earthquake of the last century was the one that occurred on March 4, 1977 ($M_{G\text{-}R} = 7.2$; $M_W = 7.5$). All the above mentioned strong seismic motions have severely affected Bucharest, Romania's capital city, where the buildings that are subject of this paper are situated. Two major events have changed the concept of building design in Romania: the first strong ground motion record obtained during the on March 4, 1977 earthquake, which revealed long period motions in Bucharest, much different from those currently adopted in the design codes based on Southern California recordings, and the change of the political regime in Romania which led to the integration of the country in the European Union. In the period between 1990÷2016 high-rise buildings were built very close to the existing old, low-rise buildings, some of them of heritage value. Up-to-date, studies on soil-structure interaction are in general restricted for a single foundation on elastic half space medium. A very few theoretical studies for adjacent buildings founded at different depths using several structural models of analysis were performed and some of the obtained results will be presented in brief. Wave propagation in layered subsoil with two adjacent foundations at different depths is very complicated. The purpose of this paper is to present the relevant aspects of an instrumental investigation carried out at the site of two adjacent buildings with different heights, structural systems and foundation levels, under ambient vibrations, and to extend the findings in the case of the peculiar strong motion generated by the Vrancea seismic source. The instrumental study has aroused major interest as, on one hand, there were no instrumental investigations for such tall buildings ever performed in Romania and, on the other hand, high-rise buildings with several basements haven't been until then the subject of a responsibly conducted research. A point of view on the possibility that a high-rise building has a negative influence on the neighboring low-rise constructions during strong future earthquakes is also presented. The instrumental investigations carried out simultaneously inside and outside the high-rise building revealed the fact that between the bulb of pressure of its foundation structure and the area of influence of the nearest shallow foundation of the low-rise building there can be no significant interaction. It was arrived to the conclusion that there will not be any notable influence of the foundation medium and of the structural physical base of the investigated high-rise building on the foundation medium and on the foundation structure of the adjacent low-rise building, during future strong ground motions.

Keywords: instrumental investigation; eigenperiod; adjacent structures; foundation; soil-structure interaction

1. Introduction

On November 19, 2014, S.C. Millenium Building Development S.R.L. with its headquarters in Bucharest, the owner of the building “Cathedral Plaza”, has requested a set of instrumental investigations for the previously mentioned building, in order to establish its eigendynamic characteristics. Furthermore, it was also requested to present (if possible) a point of view on the possibility that such a high-rise building may have a negative influence on the neighboring low-rise constructions during strong future earthquakes (Fig.1). The demand made by S.C. Millenium Building Development S.R.L. has aroused major interest as, on one hand, there were no instrumental investigations for such high-rise buildings ever performed in Romania and, on the other hand, high-rise buildings with several basements haven’t been until then subject of a responsibly conducted research. In consequence, no one knows how these tall buildings would behave at the incidence of a future strong Vrancea earthquake. Not ultimately, the instrumental investigations were carried out within a PhD program.

Fig. 1 – General view of the “Cathedral Plaza” and of “St. Joseph Cathedral” buildings

It should be mentioned that before performing the instrumental study, another Romanian company (S.C. Allied Engineers Group S.R.L.) had achieved the technical assessment of the building under debate, which didn’t contain technical information of experimental nature. This was the reason why the owner, proving good knowledge of structural dynamics, wanted to certify the accuracy of the structural analysis which was carried out, and also to have a complete picture of the structural safety of the building together with the identifying of possible influences on buildings in the immediate vicinity.

Another reason for conducting these investigations was represented by the numerous technical changes in the design legislation, following the Romania accession to the European Union. The implementation of the Eurocodes generated serious problems that will be highlighted by the occurrence of the first major seismic event. To have a picture of this disastrous situation, the words of the President of the “Romanian Association of Civil Engineers” will be given in the following:

“*An uncommon situation was reached as each design team, or even a single designer, is obliged to implement a series of technical provisions which have not yet been confirmed by the engineering practice being ambiguous, incomplete and, which is worse, having both conceptual and analysis unacceptable errors. The new standards are changed very often, but not all at the same time, aspect which brings to paroxysm the confusion in applying the design provisions in civil engineering… In trying to design, within this chaotic technical legislation, we are always at fault as whatever you design following any code (EU codes, or Romanian legislation) in the end you stand beyond the technical provisions, since no standard or prescription is complete, easy to understand and apply, have errors difficult to discover and eventually to eliminate.*”

Thus, the forced implementation of the Eurocodes in Romania has created much confusion in their application in the design process, in short, dissatisfaction at national level [1].

2. Structural description of the building

The structural system of the "Cathedral Plaza" building has in its composition a *superstructure* with a height regime GL+18L+TL, a *substructure* composed of four basements for car parking (4B), and a *foundation structure* consisting of a general mat supported by two categories of piles. If to these three components the foundation medium is added, one can obtain the image of what could be defined as the "*total structural system of the building*".

2.1 The superstructure of the building

The superstructure of the building has in its composition a *ground level* – GL (H = 4.90 m), 18 *current levels* (18 L) and a *technical level* (TL) in which there are located, among other things, the thermal station and the hoisting winch room (H = 3.60 m). The total height of the superstructure, measured from the quota ± 0.00 m to the cornice quota, is 74.50 m (Fig.2).

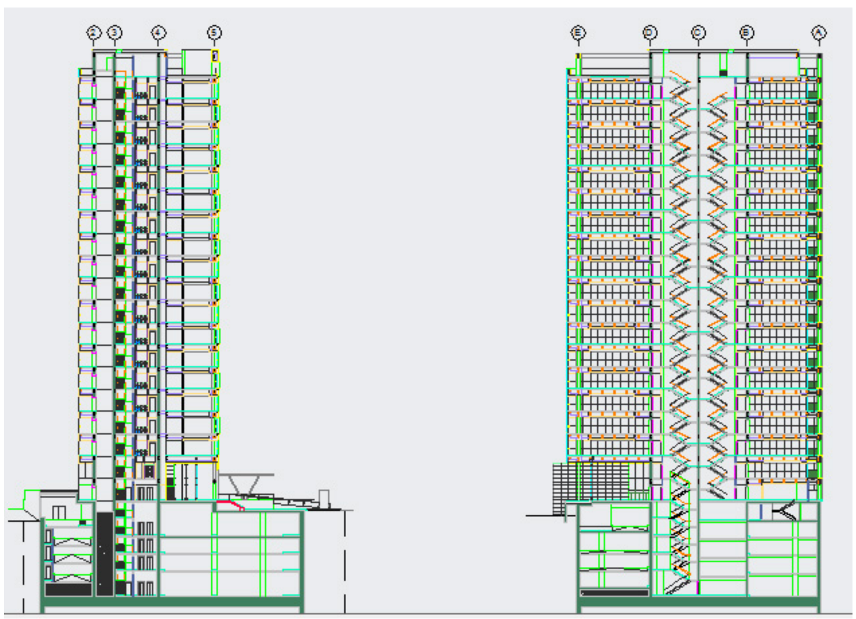


Fig. 2 – "Cathedral Plaza" building vertical sections

In a horizontal plane, the superstructure is essentially quasi-rectangular in shape, withdrawn in the south area of the property. Typical floor dimensions of the upper floors are about 42.35 m by 22.10 m. The surface of the current level is equal to approximately 903 m^2. The total unfolded surface of the superstructure is about 16,900 m^2, while the net surface is equal to 14,550 m^2, after subtracting the voids for elevators, garbage rooms etc.

The structural subsystem of the superstructure is of dual type. It is composed of a central reinforced concrete shear core of composite structural walls and perimeter steel moment resisting frames, located on the main directions of the building. The perimeter steel moment resisting frames were introduced in order to balance the lateral stiffness of the whole structural system of the building. For this purpose they are braced with steel diagonals, the diagonal panels being extended over four levels, along the axes "A" and "E", and over eight levels along the axis "5" (Fig.2).

The vertical components of the structural subsystem of the superstructure have the characteristics that are presented further on:

- *the central core of composite structural walls* is eccentrically placed as against the center of mass of each floor structure, at every level; the thickness of the core structural walls is 60 cm, excepting those of axes "2" and "4", having a thickness of 65 cm; from the functional point of view, the central core ensures the vertical circulation in the building and some technical spaces;
- *the steel columns* were embedded in reinforced concrete in order to ensure them high resistance and fire protection conditions; their cross sections are square (75 cm x 75 cm).

The horizontal component of the structural subsystem of the superstructure is formed by the floor structures. These consist of the main beams of the frame, of the secondary beams (ribs) disposed between the main beams at about 2 m apart, and of reinforced concrete plates of 13 cm thickness. The steel secondary beams are resting on the reinforced concrete structural walls of the central core and on the perimeter frames. The floor structures can be considered *rigid diaphragms* at every level of the construction.

The two components of the structural subsystem of the superstructure (the central core + the perimeter braced frames) ensure optimal transmission paths for gravity and lateral loads to the "*physical basis of the structural system*" (the assembly consisting of the substructure and the foundation structure).

2.2 The building substructure

The substructure, consisting of four levels, is designed exclusively for vehicle parking and is situated below the level +1.40 m (the ground floor level in the area of the central core). It occupies almost the entire area of the property being substantially expanded compared to the superstructure.

The structural subsystem of the substructure consists of the reinforced concrete structural walls of the central core continuing those of the superstructure, of the perimeter molded walls and, in addition, of the 18 columns that sustain the floors of the four basements, located in the substructure areas which do not have correspondence with the superstructure. It should be mentioned that all the substructure columns were achieved in "*composite column solution*" (steel columns encased in structural concrete).

The horizontal component of the substructure consists of reinforced concrete *slabs* of 35 cm thickness.

2.3 The foundation structure

Given the existence of four underground parking lots together with the large loads transmitted by the superstructure, and having in mind to limit the global influence of this high-rise construction on the buildings in the immediate vicinity, a mat foundation solution supported by two groups of piles was adopted. For the group of piles beneath the central core and beneath those columns that continue to the superstructure, piles of ∅1500 mm in diameter were provided. Meanwhile, beneath the columns that sustain the substructure piles of 880 mm in diameter were achieved.

The structural system designer (S.C. Popp & Associates S.R.L.) has been in the situation to design a reduced subsidence high-rise building, whose foundation structure should not interfere with the foundation structures of the low buildings in the immediate vicinity: "Calvineum" and "Saint Joseph Cathedral". In other words, the area of stress distribution generated in the foundation medium by the foundation structure of the new high-rise building should not significantly interfere with the area of stress distribution generated in the foundation medium by the existing low-rise buildings.

2.4 The foundation medium

In order to know the foundation medium geotechnical drillings and *in situ* dynamic penetration tests were conducted up to the depth -45 m. The general mat of 1.80 m height was achieved within the strong plastic clay layer with calcareous concretions existing between the depths -9.50 m and -24.00 m. In between the depths -24.00 m and -45.00 m (base of drillings) a layer of fine sand in a compact state was identified. The ground water level was intercepted in the existing sand and gravel layer at -7.00÷ -8.00 m.

3. Information connected to the design process

3.1 The "St. Joseph Cathedral" building

The "St. Joseph Cathedral" building is a low-rise building which was built between 1873÷1884, following the plans of the Viennese architect Dr. Friedrich von Schmidt. The in-plane dimensions of the building are: length equal to 40 m, width equal to 22 m. The cathedral building height is equal to 22 m. The central nave is separated from the lateral ones by rows of columns finished with gilded stucco, on which broken arches discharge (Fig.3).

Fig. 3 – “St. Joseph Cathedral” interior view and the shape in-plane with the stainglass windows adapted from a picture (Internet)

The lateral thrusts are taken over by exterior buttresses. The roof of the main nave, in two slopes, has the intrados with visible trusses and beams. The collateral naves are covered with monastery vaults. The portal consists of broken arches, resting on colonnades.

The “St. Joseph Cathedral” building suffered major damage during the strong earthquakes that occurred in 1929, 1940, 1977, 1986 and 1990. The damage can be attributed to the fact that the building was built in a period in which there were no technical rules and, moreover, no seismic design rules. It should also be noted that the American bombardments dated April 4, 1944, as well as the German ones of August, 24 and 25, 1944, caused significant damage to the building. After each seismic event and the episodes of war previously mentioned the building was repaired and partially strengthened.

After 1989, Professor Alexandru Cismigiu drew up a new complex project of strengthening, which was implemented during the period 1991-1994. *Consequently, the new high-rise building “Cathedral Plaza” was built near an existing low-rise building with completed retrofit works.*

An important argument justifying the “*survival*” of the “St. Joseph Cathedral” building is linked to the spectral compositions of the seismic motions occurring in the Vrancea region, which are characterized in Bucharest, so far, by long periods, while the fundamental eigenperiods of the cathedral building range in the domain of short periods. The good behavior of the thick structural brick masonry walls, with a significant dissipative function to seismic loads, has compensated the initial poor design concept of the building. All the structural interventions carried out for its strengthening have changed the values of its fundamental eigenperiods, thus leading to their shortening.

Up to the moment of writing the present paper, the “St. Joseph Cathedral” building (having in its immediate vicinity the high-rise “Cathedral Plaza” building) has undergone in very good conditions the most recent Vrancea earthquakes, with seismic magnitudes of up to $M_{G\text{-}R} = 5.8$. The reality highlights the lack of any negative influence of the new high-rise building on the low-rise Cathedral building.

3.2 The “Cathedral Plaza” building

Unlike the “St. Joseph Cathedral” building, the high-rise building “Cathedral Plaza” (built very close to the previous one) was designed and built according to all the existing technical legislation in force in the reference period. The framing, the shape optimization and its design were done taking into account the period value of the dominant component of the seismic action which occurred on March 4, 1977. Therefore, the “Cathedral Plaza” owner wanted a confirmation of both *initial design process* and of the results obtained in the two *technical assessments* drafted in 2013.

4. Can site response be predicted?

Bucharest is a dense urban environment composed of different city constructions that contain clusters of closely spaced buildings. During strong motion events, seismic waves propagate through the ground and interact with the foundation structures of the buildings which, in turn, transmit the seismic motions to their superstructures. This phenomenon is known as "*foundation medium – physical structural base - superstructure*" interaction. Obviously, for buildings located in dense urban environments, the assumption according to which these are isolated from each other is invalid, and can lead to erroneous results. The situation of adjacent buildings interacting through the ground supporting their foundations is not always well studied. This was *not the case* of the subject presented in this paper. To be more precise, a high-rise building "Cathedral Plaza" was built at very close distance from existing old low-rise buildings of heritage values, among them being "St. Joseph Cathedral" and the "Calvineum". The design team of the new high-rise building ordered a series of geotechnical and hydrological studies which formed the basis of the foundation structure choice and of its practical achievement, so that the neighboring buildings were not to be affected during the construction works, nor during the occurrence of strong future earthquakes. The foundation structure of the "Cathedral Plaza" building was presented in the paragraph 2.3. The investigations that were carried out showed that the supporting ground was free from risks of ground rapture, slope instability and permanent settlements caused by liquefaction in the event of an earthquake.

Before the completion of construction works a number of conflicting viewpoints have occurred, but in this paper only some selected aspects of technical nature are presented. Among these allegations one refers to the fact that the new high-rise building will negatively influence the behavior of the old existing ones during a strong future earthquake. Thus it has come to the eternal question, to which both seismologists and design engineers are trying to give an answer: "*Can the response of a building in a certain location to a strong seismic motion be anticipated?*" This question is directly correlated to that formulated in 2004 by the American geophysicist David M. Boore: "*Can site response be predicted?*" [2]. A number of worldwide recorded strong motions with different seismic sources, as well as the earthquakes recorded in Romania having the same seismic source, demonstrate that ground motions have large site-to-site variability for a single earthquake and large earthquake-location-dependent variability for a single site. This variability makes both site-specific and earthquake-specific prediction of site response quite uncertain, even if detailed geotechnical and geological information is available near the site [2]. The literature on site response is huge and increasing, which is a good sign that this field is still alive and well. The uncertainties associated to predictions of both "*site-specific*" and "*earthquake-specific*" site response can also lead to dangerous situations, as a result of affirmations made without any scientific basis.

It is well known that the strong seismic events which have occurred in Romania in 1977, 1986, 1990 and 2005, from the same intermediate seismic source, were recorded and it was found out that each of these had a specific spectral composition (in other words, the frequency content of each of the four seismic motions was different from a seismic event to another one). This aspect has not prevented the occurrence of an unofficial so called "*seismic map*" of the Bucharest city, which specifies for each area considered "*the value of the soil acceleration during a major seismic event*" and "*the duration of seismic motion*". This seismic map containing false information created considerable confusion at the level of the less qualified in earthquake engineering. That's why the building owner was put in a position to respond to many attacks initiated by unqualified persons, but vocal and influential on mass media.

Any attempt of a "*seismic microzoning*" of Bucharest Municipality should be based on genuine accelerograph recordings. Unfortunately such records are missing and currently there are no "*objective conditions*" for drafting a so-called "*seismic microzoning map*". Moreover, the spectral compositions of the strong seismic motions which struck Bucharest City clearly showed the fact that they were due to the "*focal mechanisms*" of the earthquakes and did not depend on the local site conditions.

5. Aspects related to the structural physical base of the "Cathedral Plaza" building

The high-rise office buildings designed in highly urbanized areas require in most cases underground levels for parking lots. That's why these are defined as "*machines that make the land pay*". The complex situations associated with deep excavations and with in-plane considerable dimensions of new buildings, must be treated very professionally in order to limit their influence on the neighboring buildings. In the case of the "Cathedral Plaza" building four underground levels resulted as necessary and, as a result, the design of the deep excavation was done using a support system with basement floors carried out in the "*top-down*" system. Firstly a sealed perimeter enclosure of reinforced concrete molded walls of 80 cm thickness was performed. The depths of the molded walls enclosure was established by the sealing conditions offered by the impermeable horizons of the consistent plastic clay layer existing at -21.00 m. The molded walls were "*locked*" by the underground floors as the excavation kept on going in depths, thus their possibility of lateral deformation being eliminated. To reduce the risk of the foundation medium deformation during the execution of the molded walls, the layer of sand and gravel on the site perimeter was reinforced by injecting a solution containing stabilizing agents. In addition, to prevent the risk of possible ground collapse on the adjacent side of the wall of the "St. Joseph Cathedral" building, prior to the completion of the molded wall, panels with reduced lengths of 3.5 m were carried out.

As a consequence of all the prevention measures considered in the design process, lateral displacements of the molded walls under the earth pressure loads of 2…4 mm have resulted (for distances in the range 1.00…10.00 m). The stress and deformation states of the foundation medium under the new building haven't significantly changed, as the average pressure exerted by the building over the foundation medium was approximately equal to the geological load eliminated by the excavation of the earth up to a depth of 15.00 m. The probable settlement of the new building, which was computed according to the legislation in force, resulted equal to 4 cm. The foundation medium settlement in the area of the outer wall of the "St. Joseph Cathedral" building resulted equal to about 8 mm, and in the area of the first raw of columns in its interior resulted equal to 5 mm. All these settlement computed values, many of them confirmed by direct measurements, were lower than those stipulated by the technical norms in force at the time of design.

The solution adopted for achieving the structural physical base of the "Cathedral Plaza" building (substructure + foundation structure) resulted in a minimal disturbance of the stress state and of the deformation state in the foundation medium associated to the works. This statement is based on the fact that during the construction works no damage was reported either inside or outside the "St. Joseph Cathedral" building. On the enclosure side next to the "St. Joseph Cathedral" building (west side) "*the wall displacements and the foundation medium settlements were lower than those of the other sides, probably due to the favorable effect of the additional screen created by the series of injections that have been made in the non-cohesive layer at the site boundary, prior to the start of the completion of the molded walls. The only topographic gauge on "St. Joseph Cathedral" building showed a low settlement (0.7 mm), very close to the limit of the measurement accuracy*".

6. "Cathedral Plaza" building instrumental investigations

The need to perform instrumental investigations on the "Cathedral Plaza" high-rise building had mainly the following reasons:

- complaints made about its possible unfavorable behavior at the incidence of a future strong earthquake;
- the tendentious presentation of some measurements performed in the "St. Joseph Cathedral" low-rise building by a team from the "Osservatorio Sismico A. Bina", Italy;
- the identification of possible differences between the finite element analysis and the experimental vibration data;
- obtaining useful instrumental information based on the ambient response of the adjacent buildings founded at different depths;
- establishing the degree of structural performance of the "Cathedral Plaza" building.

At present, there is a dispute in court between the owners of the two buildings. In brief, the lawyers who represent in court the "St. Joseph Cathedral" asked for the "Cathedral Plaza" building to be demolished. Beside some arguments related to the alleged violation of construction documents (which are not subject of this paper), there are accusations according to which the high-rise building would endanger the low building during a strong earthquake. To be more convincing, the Cathedral representatives ordered a low-level vibration testing of their building and of the area in its vicinity. In its turn, the owner of the "Cathedral Plaza" building, proving responsibility, conducted the technical assessment of the construction and verified the obtained results based on different structural models of analysis through a "*structural identification*" by instrumental investigations.

As it is well known, the structural performance of a high-rise building depends on its stiffness and mass distribution, and may be assessed using programs based on finite elements. The structural models of analysis are "*idealizations*" more or less effective and can be checked (confirmed) at a given moment by the dynamic action of a strong wind or a severe earthquake. Obviously it is preferable that they should be validated before the occurrence of such a major event. The designers should be extremely interested to ascertain if their projects were accurately implemented in practice, and the investors to know the "*structural performance*" of each of their financed buildings that are to be exploited.

Both international and national experience have however shown that the structural models of analysis based on finite elements are often failing to provide accurately the fundamental eigenperiods of vibration of the high-rise buildings, regularly resulting with overestimated values. This aspect has resulted from instrumental investigations which revealed that the fundamental eigenperiods of vibrations in the case of high-rise buildings are significantly shorter than those obtained by structural analysis, meaning that the buildings are stiffer than they were anticipated to be in the design process. The problem that stands in front of such a situation must be explained by technical arguments and the main aspect that needs to be elucidated is the design process itself. The main causes that lead to such a discrepancy could be assigned to the structural models of analysis which rarely take into account in an accurate manner the torsional effects under all their aspects, as well as to the behavior of the assembly "*substructure – foundation structure – foundation medium*" under dynamic loads.

A complete understanding of the structural performance in the linear range of a high-rise building to lateral loads can be obtained only through the instrumental evaluation of its eigenmodes of vibration.

6.1 The objectives of the instrumental investigations

The main objectives of the instrumental investigations carried on the "Cathedral Plaza" building were related to the following aspects:

- a dynamic characterization of the structural properties of the whole building, with the intent to diagnose its own "*dynamic identity*";
- the identification of the eigendynamic characteristics of the building from ambient vibration tests (eigenperiods, eigenshapes, overall damping);
- the identification of possible elastic and/or inertial discontinuities;
- pointing out the vulnerable potential areas of the building to future seismic actions;
- the checking of the accuracy of the structural models of analysis used in the design process;
- the correlation of the instrumental information with that obtained by structural analysis;
- the identification of possible influences between the investigated building and the adjacent ones;
- the interpretation the results obtained by instrumental investigations.

6.2 Short on ambient vibration measurements [3]

The Earth's surface is in a nearly continuous state of agitation. This motion provides the low amplitude, irregular wave pattern, known as "*seismic noise*", which constitutes the normal background of oscillation of seismograms.

The microseismic background at any given site on the Earth is comprised of energy generated from multiple simultaneous sources. The energy arrives at the site from several directions in the form of mixed wave types, propagating in different ways. In addition, the energy is relatively continuous with time and in many cases of very low level. The result is a phenomenon that is very difficult to successfully model and quantitatively analyze.

The source of the seismic noise can be classified into two major subdivisions: those that result from mankind's activities (*cultural noise*) and those that occur naturally (*microseism*).

The term "*cultural noise*" is used to describe any seismic noise associated with man or man-made machinery: operation of power plants, factories, trains and highways. Cultural noise is in principal avoidable, although it is often impractical to site stations at sufficient distances away from cities or highways. These activities create vibrations in the Earth surface that can propagate for quite large distances to appear as *cultural noise*.

Cultural noise is primarily confined to the short period interval of the spectrum (period less than 1.0 s) due to the inherent mechanical properties of most machines (finite physical and relatively high rotational speed of most equipment). Noise of this type tends to attenuate quite rapidly with distance.

The other sources of the Earth noise are those that occur naturally, called *microseisms*. Early seismographs were strong motion instruments, showing little or no response to week earthquakes or *microseisms*. Probably the first discussion and the naming of microseisms can be traced back in 1874. The history of the search for the origin of microseisms is extensive, and new results appear periodically in literature. However, enough is known to formulate a fundamentally sound picture of the sources of the microseismic background between 0.01 and 1000 s.

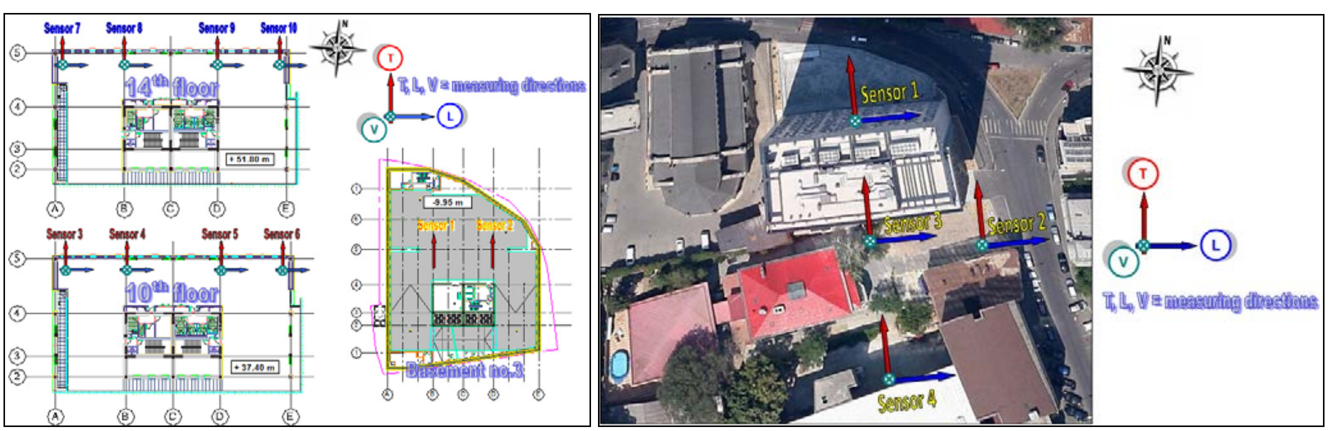
The following explanation of the origin of the microseismic background in the author's interpretation might have as starting point "*the earthquakes*". As it is known, earthquakes are caused by tectonic forces that press the lithosphere until it breaks. These forces are present day and night and are also the cause of microseisms. That's why microseisms are always present everywhere, and come at a particular site from many different directions. Since every part of the Earth's lithosphere is in struggle with the squeezing forces, it becomes source for microseisms.

A definition of the microseism can be given as follows: a continuous ground motion constituting the background noise at a particular site for any dynamic/seismic measurement. Microseisms with periods shorter than about 1.0 s are usually caused by artificial sources such as traffic and machinery.

In conclusion, the ground at a particular site is continuously in a state of low amplitude motion due to various natural and cultural disturbing factors. Ambient vibrations have a random nature and cover a relatively wide band of frequencies [3].

6.3 Experimental study data

To obtain the necessary information for the proposed objectives, several acquisition configurations were performed. 10 sensors were placed in five sets of measurements within the building, and 4 sensors were used for the identification of possible influences between the investigated building and the adjacent ones. In setting the location and orientation of the sensors (Fig.4) it was kept in mind the shape in-plane, as well as the vertical configuration of the building. Simultaneous measurements were made, with sensors inside the building (at the ground floor and at the 3rd basement) and outside it (at natural ground level at 10.00 m, 20.00 m and 50.00 m and in two low-rise buildings where access was granted). Typical time domain recordings and the corresponding amplitude Fourier spectra are shown in Fig.5 and Fig.6.



a) b)

Fig. 4 – Different configurations of sensor locations, inside (a) and outside the building (b)

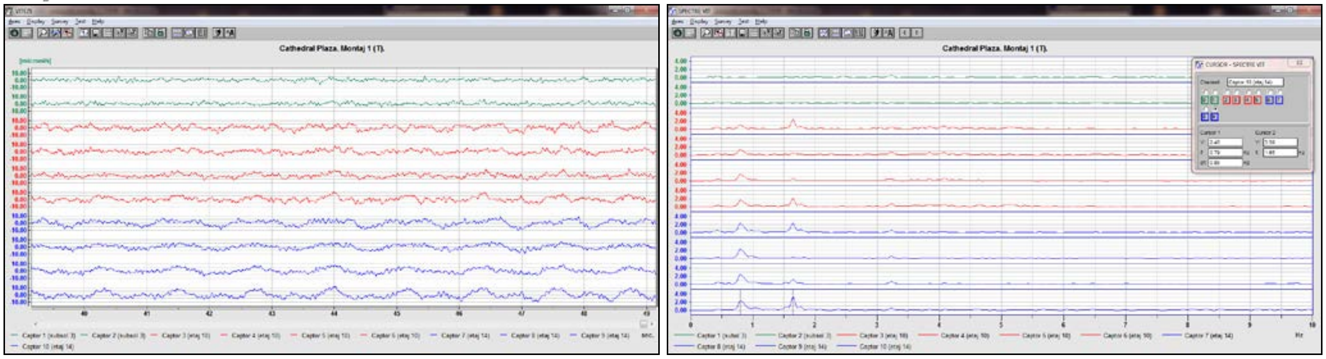
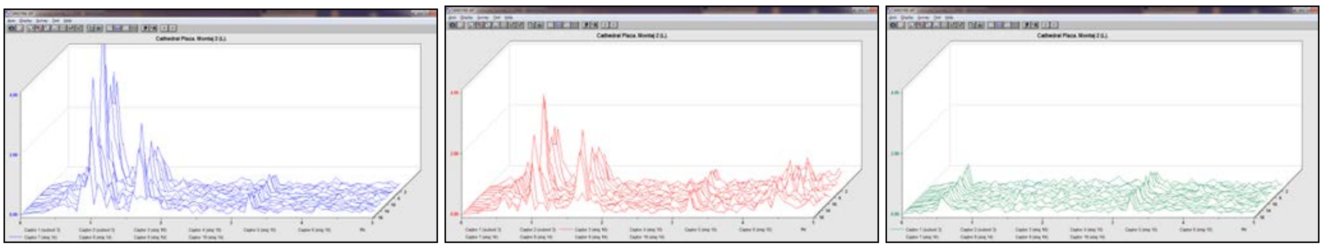


Fig. 5 – Ambient vibration test. Time domain and corresponding Fourier amplitude spectra (T direction).



(a) (b) (c)

Fig. 6 – Ambient vibration test. Running Fourier amplitude spectra. (a) Sensor at the 14th floor. (b) Sensor at the 10th floor. (c) Sensor at the 3rd basement level.

6.4 Some conclusions after performing the instrumental investigations

After performing the complex program of acquisition, processing and interpretation of the instrumental data, the following conclusions were formulated.

a) The instrumental investigations mainly refer to the behavior of the “Cathedral Plaza” building in the linear elastic range, due to the limitations imposed by the low level of stress given by the excitation source associated to ambient vibrations.

b) The recorded signals revealed the *synchronism* of the motions in the various instrumented points, fact that proves that the two subsystems of the superstructure work together.

c) The following fundamental eigenperiods of vibration were obtained: $T_{1,T}$ = 1.26 s; $T_{1,L}$ = 1.02 s; $T_{1,V}$ = 0.41 s; $T_{1,TORS}$ = 0.61 s, emphasizing a higher degree of flexibility on the transverse direction. It was found out that these eigenperiods pertain to a relatively narrow range of variation, which proves the fact that the building has a behavior in the elastic range quite homogeneous on both horizontal directions. The absence of other higher eigenfrequencies of vibration proves that the building has a well defined *dynamic identity*.

d) The fundamental eigenperiods of vibration range in a domain of values shorter than expected for such buildings, but are compatible with those obtained by the structural analysis performed by the design team, as well as by the authors of the technical assessments. The short values of these periods are the result of using composite structural elements and steel bracing within the structural system of the superstructure.

e) The instrumental investigations have certified that the floor structures of the 10th and 14th levels fulfill the role of rigid diaphragms. The processing of the recorded signals put to evidence a coupling between the vibrations of the building on the two main directions, which revealed the existence of an overall phenomenon of torsion. The obtained result can be extended to the other over-ground structural floors, but not for the floors of the substructure, aspect which strengthens the image of a rigid and resistant structural physical base.

f) Based on the autocorrelation functions, the values of the critical damping obtained through typical data processing are in the range 4.06%...5.32%, values considered appropriate for this building with a dual structural system, with both RC structural walls and perimeter columns completed in composite solutions.

g) The recorded signals processing, associated to those configurations with a sensor inside the "Cathedral Plaza" building and other three sensors outside the building, revealed spectral compositions characterized by wide band frequencies. Certain spectral peaks were found in all computed amplitude Fourier spectra (e.g. 2.26 Hz and 3.23 Hz). Obviously, these frequencies are appropriate to some components of the ambient vibrations, which increase their importance in the vicinity of the low-rise building eigenfrequencies.

7. Some comments and conclusions

A tectonic earthquake is a unique, interesting and challenging natural phenomenon. Earthquakes that occur in the Vrancea seismic region are singular seismic phenomena in the world. Bucharest is the largest city affected by these earthquakes and it is located at the surface of a sediment-filled basin of 1.5 km depth. Both mentioned aspects, i.e. "*a large city*" and "*atop sediments*", considerably increase the earthquake hazard. As seismic wave interference and resonant phenomena in sediment-filled basin can produce anomalously large earthquake motions at the Earth surface, the so-called "*site effects*" can occur.

Two phenomena are associated with the local abnormal effects of the earthquake motions: their amplitudes can be considerably amplified and the duration of the strong motion can be significantly increased. These undesirable effects can occur for certain periods at which buildings or other construction types can be damaged or destroyed. The seismic wave interference and the resonant phenomena led during the 1940 and 1977 earthquakes to disastrous effects.

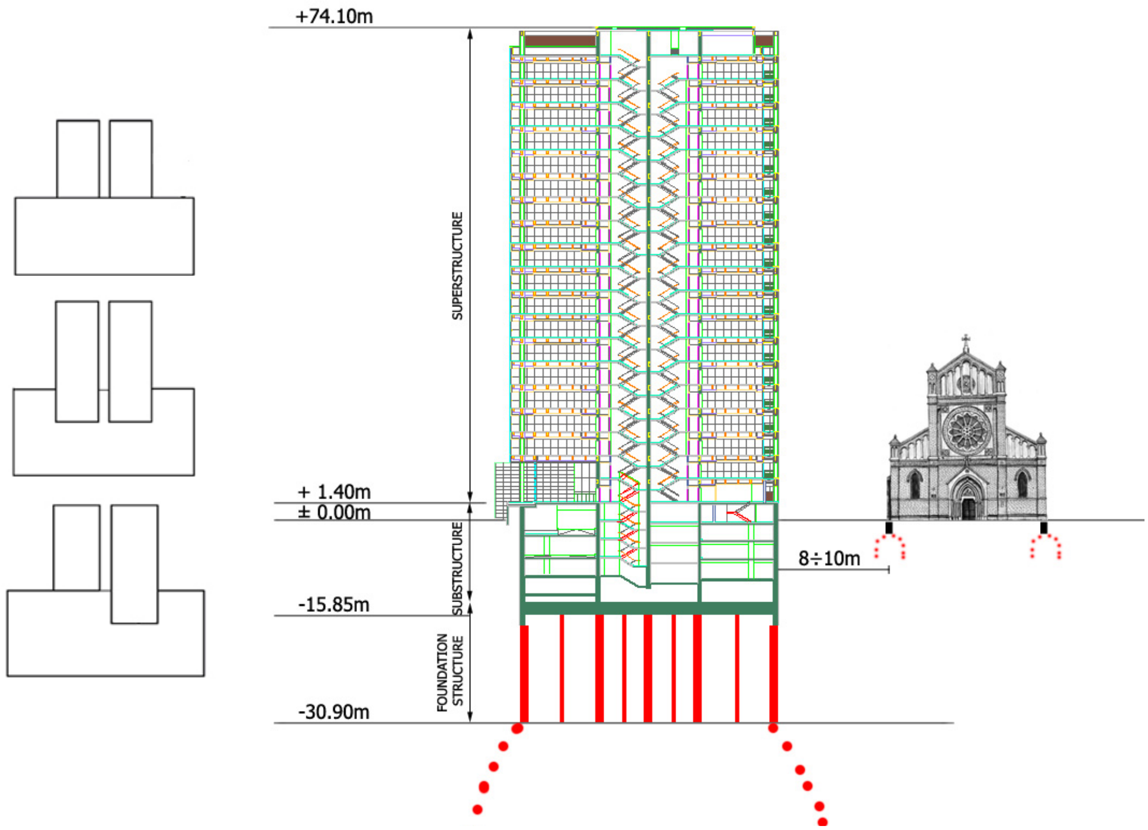
A high-rise building achievement always causes the deformation of the foundation medium, both inside and outside its perimeter. The change of the state of stress and of the state of deformation within a foundation medium defines what is known as "*zone of influence*". The current generation of technical regulations contains limitations for the foundation medium deformations only for buildings with intact structural systems, without referring to the existing buildings that were built with no technical norms, and which have undergone damage during the strong earthquakes that they have supported in time.

The study of the interaction of two adjacent buildings with their foundation structures at different depths during a strong earthquake was subject of a limited number of papers. One of the recent studies [4] considered the three cases presented in Fig.7,a. The authors considered a building in a particular location which resisted static and dynamic loads along its lifetime. As a new building was built next to the old one, it was considered necessary to examine the interaction between the two buildings (with the same height) considering three different plane models. The findings of the study led to the following conclusions [4]:

- if the two neighboring buildings have shallow structures of foundation at the same level, the interaction between them is small and negligible;
- if the two neighboring buildings have deep structures of foundation at the same level, then due to interaction the forces in one building are 25% larger than those in a single such building;
- if one of the two buildings has its foundation structure of "*shallow*" type and the other one has its foundation structure of "*deep*" type then, as a result of the interaction between them, the generalized forces in one building are 20% lower than those corresponding to the building having a shallow foundation structure.

In the case of the two buildings which are the subject of this paper (Cathedral Plaza and St. Joseph Cathedral) their heights are different and their foundation structures are at different depths. The low-rise building was recently strengthened. During the construction of the "Cathedral Plaza" building and the period after its completion, no damage was reported in the interior and exterior of "St. Joseph Cathedral" building. Some research using the modified Boussinesq equation for determining the impact of the foundation medium of a new construction against the foundation medium of an existing one is envisaged.

The instrumental investigations carried out simultaneously inside and outside the "Cathedral Plaza" building revealed the fact that between the bulb of pressure of its foundation structure (starting at -30.90 m) and the area of influence of the nearest shallow foundation of the "St. Joseph Cathedral" building there can be no significant interaction (Fig.7,b).



(a) (b)

Fig. 7 – (a) Three foundation arrangements [4]. (b) Foundation structures zones of influence.

The future strong seismic motions generated by the Vrancea earthquake source and characterized by long periods (specific for constant epicentral distances of about 160 km) will affect buildings that have eigenperiods of vibration in the vicinity of the periods of the dominant components of the seismic waves. Therefore the high-rise building "Cathedral Plaza", was optimized and designed in such a way in which it would have fundamental eigenperiods of vibration on both main directions of about 1.00 s, which is relatively far from the known value of the dominant period of the seismic waves generated by the March 4, 1977 earthquake. On the other hand, the low-rise buildings characterized by short eigenperiods of vibration, as in the case of the "St. Joseph Cathedral" building, can't be affected by Vrancea type seismic motions, except for the situation in which they have hidden damage or have not beneficiated of a strengthening solution, accurately designed and properly put into work. In other words, both the high-rise "Cathedral Plaza" building (due to its design) and the "St. Joseph Cathedral" building (due to its height) should not be affected by long period Vrancea seismic motions. This aspect justifies the assertion that there will not be any notable influence of the foundation medium and of the structural physical base of the "Cathedral Plaza" building on the foundation medium and on the foundation structure of the "St. Joseph Cathedral" building.

8. References

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