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SOIL CONDITIONS AND STRUCTURAL TYPOLOGIES FOR SEISMIC ISOLATION OF BUILDINGS, IN CITIES EXPOSED TO STRONG EARTHQUAKE HAZARD

Stefan Florin BALAN, Bogdan Felix APOSTOL, Alexandru TIGANESCU

National Institute of R&D for Earth Physics,
12 Calugareni Street, Magurele, Ilfov, Romania

Corresponding author email: sbalan@infp.ro

Abstract

Some buildings need special attention in attempting to protect them against strong seismic movements. Seismic isolation comes as a suitable solution to protect the integrity of the construction. For this accomplishment are needed some thorough data about the dynamic characteristics of the structure and site specificity. The characteristics of the buildings can be found from either design data, or from subsequent measurements on its structure. The study of seismic waves has become a design criterion in advanced seismic codes, using design spectra compatible with local conditions differentiated on qualitative stratigraphic description and quantitative waves velocity-based criteria. The results of the later important geophysical measurement campaigns are described and used in this work. To identify whether seismic isolation for buildings is efficient in an earthquakes-prone environment, very important is the analysis of the location they are, or will be. One of the most important elements to be evaluated is the natural period of the site. The conditions for an efficient seismic isolation are presented and discussed with examples. In the paper are also described the different types of seismic isolated structures in Bucharest, and the reason for selecting them.

Key words*: earthquake, foundation, fundamental period, seismic isolation, structural damage.*

INTRODUCTION

The current seismic design of structures is based on the following safety principles and requirements:

- the structure must withstand minor earthquakes without damage;
- medium earthquakes allow damage to non-structural elements but not to resistance elements;
- structural damage is allowed for major earthquakes, provided that collapse is avoided.

Structure's strength can meet the above requirements if they have sufficient resources to dissipate the seismic energy transmitted by the movement of the foundation ground. This dissipation is the result of the ductility of the structural elements, inelastic and residual deformations (allowed in certain areas provided in the design), to which is added the dissipation of seismic energy given by the degradation of non-structural elements.

The dynamic isolation of the buildings from its foundation is an old desideratum of structural design. Theoretically, if a perfect decoupling between the structure and the supporting ground were achieved, during an earthquake the movement of the ground would not be transmitted to the structure, which in this case could have only a rigid body displacement (Figure 1).

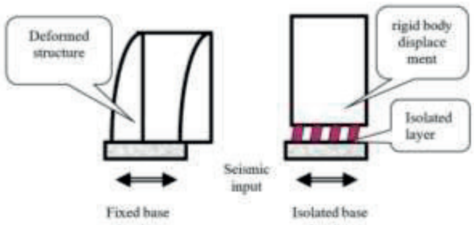

Figure1. Fixed base versus isolated base

In reality, a total decoupling, a total isolation of the structured base is practically not possible. Any isolation layer introduced between the ground and the structure cannot be completely decoupled due to the inherent frictions through which the seismic movement will also interact with the structure, but to a much lesser extent.

However, an insulating layer with low horizontal rigidity reduces the seismic force transmitted to the structure. In this sense, the notion of seismic isolation is now used. Seismic isolation systems have been developed and applied in order to distribute the deformability and dissipation processes to the isolation layer, thus protecting the structure which in this case has a reduced deformation, practically close to the rigid body behaviour.

How is decided for isolating a structure

In order to apply an isolation method to a structure it is important to understand how this procedure works, because this implies an extra effort from the design and building execution process.

The flexibility introduced by the isolation layer in the structural assembly (foundation + isolation layer + structure) makes the structure's own period suffer a jump to higher values (period shift), a jump that removes the structure from the dangerous area of the fundamental period of the site, thus avoiding destructive effects due to the resonance of the dynamic system.

Isolation of the base by introducing an insulating layer with reduced horizontal rigidity has as a consequence a flexibility of the whole structure-isolation layer-foundation and the new structure acquires its own longer period than the same structure but with a fixed base.

Due to this sense of leap - only for longer periods - base isolation is not a universal remedy applicable to all types of structures and locations. The solution must be adapted to each case according to the dynamic characteristics of the structure, of the terrain on which the structure rests and according to the predominant periods of the seismic input.

In order to illustrate this, in Table 1 is given a classification of structures, based on approximate fundamental periods and in Table 2 a classification of the soil of the sites based also on approximate determinations of own periods.

Table 1. Fundamental periods for some types of structures

Type of the structure	Fundamental period of the building T_0 [s]
Rigid (low, massive constructions, with strong vertical elements such as: ground floor halls, GF + 4, piles, abutment, etc.)	0-0.7
Semi-rigid (reinforced concrete multi-storey buildings, silos, water towers, chimneys, etc.)	0.7-1.5
Flexible (multi-storey buildings with metal frame, towers, radio antennas, etc.)	> 1.5

Table 2. Fundamental periods for some types of soil

Type of the soil	Fundamental period of the soil T_0 [s]
Rocks, consolidated alluvial deposits	0-0.7
Poorly consolidated alluvial deposits	0.7-1.5
Unconsolidated alluvial deposits, fillings	> 1.5

MATERIALS AND METHODS

Methods to determine fundamental period for buildings and soil deposits

Buildings are not independent elements, they are located on a site, upon which depends their dynamical behaviour in strong earthquakes.

- Fundamental period in buildings.

There are two categories of buildings which could be isolated: i) new and ii) old ones. In both cases, among other parameters, it is necessary to have an evaluation for the fundamental period of each structure.

i) For the new buildings, the fundamental period would be estimated from the design computations.

ii) For the old ones, in order to determine the fundamental period, several methods can be employed, based on vibration measurements.

These techniques are of interest for earthquake-prone areas, case in which monitoring is performed through ambient vibrations recordings, but also through seismic ground motions where they are available.

For both new and old buildings, the dynamic parameters, computed based on numerical models can be validated with experimental data. From the practical view-point, the values of these parameters can be used as a proxy for damage detection or can validate that the construction process has followed the rules prescribed by the design plan. In addition, for the case of the earthquake protection systems (such as seismic base isolation), the improvements in terms of structural response can be quantified and the performance of the isolators can be assessed, based on real data. In Romania, the process of computing the fundamental period of the buildings using seismic sensors is gaining more attention in the last years, given that the building stock consist of a lot of typologies, from different periods and for each of them the engineers should assess as best as they can their dynamic parameters in order to estimate its response to strong earthquakes and to prevent their collapse and extend their serviceability.

- Fundamental period in soil deposits

One of the main geophysical characteristics of a site is its fundamental period of vibration. In this sense, some of the most common methods of finding this specific period of each location will be presented.

Geophysical measurements in Romania have developed in the last decades, on a large scale, for acquiring more data about the subsoil mainly by promoting down-hole measurements, in boreholes financed within internal and external collaborations.

Since the 1990s, the profile of seismic waves has become a design criterion in advanced seismic codes, using design spectra compatible with local conditions.

Numerous drillings and down-hole tests have been carried out in the last decades in the Bucharest metropolitan region by UTCB, INCERC, GEOTEC S.A., CNRRS and other institutions. Thus, at INCERC, three reference drillings were made: INCERC 1 at 50 m depth, INCERC 2 at 70 m depth and INCERC 3 at 205 m depth (in 1998 with Romanian (UTCB) and German financing within the joint German-Romanian program of research SFB 461, "Strong earthquakes: a challenge for geosciences and civil engineering", Karlsruhe University.

The most recent research was carried out within the Science for Peace Project 981882 - "Site-effect analyses for the earthquake-endangered metropolis Bucharest, Romania" (2007-2009), a consortium formed between INCDFP and the University of Karlsruhe (Collaborative Research Centre 461 Strong Earthquakes) (Wenzel, 1997, SFB 461, 2007), UTCB also contributed to the project. (NATO SfP Project).

Within the project, for the study of the basement of the Bucharest Metropolis and the collection of data in areas with little or not at all explored so far, were carried out 10 drillings with a depth of 50 m in which 10 down-hole measurements were performed for longitudinal (Vp) and shear (Vs) seismic waves velocities. Disturbed and undisturbed soil samples (400 in number) were extracted from the 10 boreholes, on which static and dynamic geotechnical investigations were carried out. (NATO SfP Project). This high-quality seismic dataset provides important information useful for the seismic hazard evaluation across the interest area. (Balan et al., 2020a, b) Also, was carried out a continuously monitoring of the buildings, which offer data from the micro tremors, vibration and the noise. (Tiganescu et al., 2019).

In order to identify the buildings that would require seismic isolation, first it is necessary to know the dynamic characteristics of the structure, and then is needed a geotechnical and geophysical analysis of the site they are or will be constructed.

The study of the propagation of seismic waves from the seismic source to a certain point located inside the earth or on the free surface is a fundamental problem in seismology. The main aspects of interest in relation to the phenomenon of seismic wave propagation in a certain area or in a delimited location are the following: the variation of the seismic wave intensity depending on the physical-mechanical and dynamic properties of the propagation environment and the modification of the seismic response of structures depending on the local deformability characteristics of the site-specific soil deposit. Also, the importance of the site conditions is considerable, the effects of earthquakes on constructions can be amplified or dampened significantly compared to those considered in the design if not taken into account all the dynamic characteristics of the foundation -soil and soil stratification above the bedrock.

The use of seismic methods to investigate the soil deposit has proved effective in providing data whose interpretation allows the quantitative evaluation of the elastic-dynamic constants of rocks and soils and assessments of their physical condition.

The evaluation of the dynamic characteristics of the soil deposit involves the determination of the propagation velocities of the longitudinal (V_p) and shear (Vs) seismic waves and of the earth density (ρ), from which the dynamic modules of longitudinal (E_d) and transverse (G_d) deformation can be calculated, function of specific deformation induced by strong seismic movements.

Seismic shear waves define motion parameters that produce the most important dynamic effects on buildings located on the free surface of the land. It is found that the propagation velocities increase both with the degree of compaction and the physical-mechanical qualities of the soil, as well as with the depth measured from the free surface (the thickness of the considered layer) (Kramer,1996). The knowledge of the local geological conditions (subsoil) together with the information related to the distribution of the shear waves velocity in Bucharest layers allowed for upgrade the maps that display distribution of the predominant period of the upper sedimentary layers.

The velocity model constructed upon geophysical measurements indicates soft soil conditions (shear wave velocities $V_S < 360$ m/s) for several tens of meters underlain by layers of stiffer soils ($V_S > 360$–700 m/s) down to a depth of several hundreds of meters (Mândrescu et al. 2008).

Following soil classification proposed by Eurocode 8 (EN 1998-1, CEN 2004), the “deep deposits of dense or medium-dense sand, gravel of stiff clay with thicknesses of several tens to many hundreds of meters” are classified as soil type C, and the average shear waves velocity between 180 and 360 m/s.

In general, in the study of the soil deposit response during earthquakes, the importance of seismic shear waves is given, which are strongly influenced by superficial soft sedimentary deposits. However, it should be mentioned that when following the characterization of the movements with periods between 1s and 10s, the consideration of the surface layers is no longer sufficient. In such cases it is necessary to take into account the sedimentary layers up to the "seismic bedrock", which can mean sediment thicknesses that can have several kilometres.

Even in the simplified evaluation of the fundamental period of vibration in the elastic field, the depth considered in the calculation has a significant effect.

In the case of stratified deposits, consisting of n layers with different, but homogeneous properties and thicknesses, the weighted average velocity of the shear seismic waves is calculated according to (P 100-1/2013):

$$\overline{V_S} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{v_{si}}}$$

n - number of strata, d_i - thickness of every strata and v_{si} - shear velocity in each stratum.

The fundamental period of the soil deposit in a location is an important parameter in the study of the seismic response using recordings of the waves that cross the soil deposit. The fundamental period of a package of "n" layers, of total thickness H depends on the velocity of the seismic shear waves (Vs) through the layers, $T_0 = 4H/V_S$ (Mândrescu et al., 2008).

It is found that the predominant periods are directly proportional to the depth of the H deposit and inversely proportional to the propagation velocity of the shear waves. It is obvious that at equal depths H, the predominant periods will be even smaller as the soil will have higher consistency and degree of compaction.

The highest amplification in the soil deposit occurs at fundamental or lower natural frequencies, which corresponds to the characteristic period of the site.

In situ measurements of the shear wave velocities of the soil and of the thickness ensure the direct determination of the fundamental period of the soil deposit.

Seismically isolated buildings in Bucharest

The seismically isolated buildings currently in Bucharest, with some characteristics (address, number of stories, construction year, and materials) are presented in Table 3 and their photos in Figures 2-4. These buildings are permanently monitored by the National Institute of R-D for Earth Physics (INCDFP) with seismic accelerometers at different levels (status at 31.12.2020) (Table 3).

An analysis of the amplification, in the Fourier domain, from the base to the top of the building was performed, for specific frequency intervals. These three buildings are equipped with base-isolation and damping systems, and the performance of this earthquake-protection system during earthquake was assessed. (Balan et al., 2020a).

The Bucharest City Hall building (PMB) and Victor Slăvescu building (ASE) were constructed at the beginning of XX^{th} century, when no seismic design regulations were in force.

Table 3. Seismically isolated buildings in Bucharest (general characteristics)

No.	Name of building	Address	Number of stations in the building	No. of floors	Year of construction	Structural system
1	General City Hall of Bucharest (Figure 2)	Bucharest; Regina Elisabeta Boulevard no. 47	4 accelerometers, in real time, ground floor, floor 2, 3 and attic, it should be noted that all are placed above the seismic damping system of the building	UG+ GF+3F +Attic	1906. The building was consolidated after 2010 and was equipped with seismic insulators in the basement	Brick masonry with reinforced concrete floors with turned caissons
2	Arch of Triumph (Figure 4)	Bucharest; Arch of Triumph Square	2 accelerometers, one on the ground floor and one on the arch at the top, data are transmitted in real time		1921	Concrete, masonry
3	Victor Slăvescu Building, Academy of Economic Sciences (ASE) (Figure 3)	Bucharest; Calea Griviței 2-2A	monitored with two off-line accelerometers and are located in the basement below / above the seismic insulators	UG + GF+ 2F + Attic	1905	Brick masonry with truss roof

Figure 2. General City Hall of Bucharest

Figure 3. Victor Slăvescu Building, Academy of Economic Sciences (ASE)

On the ASE building, both sensors are located at the ground level, one is under the seismic isolator, coupled with the ground, and the other one is above the isolator, coupled with the structure.

For the Bucharest City Hall all the sensors are installed on the structure and the insulation system is placed under the sensors in the basement (Balan et al., 2020a).

Another structure is the Arch of Triumph (ARC), a unique structure representing a historic monument built back in the 1930s. On this structure two accelerometers are installed, one at the base and one at the top of the structure. Here the insulation system is placed under the sensor in the basement.

Figure 4. Arch of Triumph

RESULTS AND DISCUSSIONS

By comparing data from Table 1 and Table 2 an approximate, but not far from reality, results both the applicability and the limitations of the method of isolating the base:

• Isolation of the base is effective in cases where resonance with the ground can be avoided by increasing the structure's own period (positive period jump);

• The suitable candidates for the application of the method are the rigid or semi-rigid structures at their location on consolidated lands;

• It is not recommended to isolate a structure with its own period different from the predominant periods of the site;

• The inappropriate application of base isolation, when the periods of the structure and the ground are spaced apart, can have an adverse effect, it could transfer the structure from a safe area to a dangerous area.

All the seismic isolated buildings in Bucharest were isolated after construction, in the rehabilitation process, the Town Hall and Arch of Triumph being historical monuments.

The influence of the insulating systems has proved to be a solution for some older structures. The strongest events included in the analysis were one seismic event of M_W = 5.5 (October 2018) and one of M_W = 4.8 (January 2020). The structures dynamic behaviorrevealed a reduction or small amplification of motionabove isolator in comparison to the motion under isolator, and a reduction/amplification of the building base, on different period ranges, when compared with free field recordings. In the latter case the distance from the structure to the free-field station could be an influencing factor. All the data recorded on instrumented structures during seismic events, together with the mentioned analysis, can represent a reference study for future earthquakes with similar or higher magnitude.

Other matters of particular importance in judging the appropriateness of seismic isolation of an existing or future building is the consultation of maps of the fundamental period of the soil and the variation of accelerations on the surface of the city. From these maps it can be evaluated where in the city are most dangerous zones. (Bratosin, 2005; Marmureanu et al., 2010). High accelerations could produce damage to certain buildings, these could be:

a) new ones, buildings important to function after a strong earthquake (hospitals, administrative, first responder's headquarters and storage buildings, etc),
b) old buildings which in the process of rehabilitation the structural engineers decided seismic isolation a method for mitigation seismic risk (the case of isolated constructions in Bucharest).

The spots or certain areas inside the city where the approximate fundamental period of the soil deposit is correlated with the predominant period of the building which is or will be on that site, gives us the possibility to decide, among other criteria, if it is worth to seismic isolate that building or not (Bratosin et al., 2017).

The results of seismic isolation of a structure could mean change in its dynamic behaviour. Extracting the structure from the resonance area by changing upward its own period could bring an appreciable reduction in dynamic amplification. Considering as dynamical characteristics for a test structure, for example at resonance state its own period T_0=0.3 s and a damping ratio $\varsigma = 5\%$, the dynamic amplification factor could reach the value $\Phi = x_{\mathrm{d}inamic} / x_{static} = 10$.

Under these assumptions by introducing an insulating layer with certain dynamical characteristics the fundamental period, can get a jump, supposing from $T_0 = 0.3$ s to $T_0 = 0.5$ s, therefore corresponding dynamic amplification decreases dramatically from $\Phi = 10$ to $\Phi = 1.56$, in the conditions in which the excitation period remains the same (Bratosin, 2005).

CONCLUSIONS

The applicability of the base insulation technology is conditioned by the presence of three conditions:

• If the technology is necessary, imposed by the degree of seismic classification of the site and by the requirements of post-seismic functionality;

• If the structure is suitable for base isolation technology, it is a rigid or semi-rigid structure intended to be located on a land with predominantly short periods and the flexibility introduced by the isolation layer should not endanger the behaviour of non-seismic side loads (powerful winds);

• If the additional cost given by the introduction of the isolation layer and its maintenance is justified by the savings achieved from the reduction of structural requirements, by the reduction of post-seismic rehabilitation costs, by the reduction of material and human losses.

The brief enumeration above shows that the applicability is restricted to regions with high seismic potential and conditioned only by the technical conditions imposed by the dynamic characteristics of the structure and location. It is obvious that once these conditions are met, the base isolation technology also has economic justification even if we refer only to material costs and do not take into account human losses.

The base isolation technology is much more efficient if it is provided from the design stage of some structures to be made. In this case, savings can be made at the initial costs of the structural system, time savings and the achievement of the isolation system is much easier.

If the technology is intended to be applied to existing structures, complications may occur due to the implantation of the isolation layer and the change in the behaviour of the structural system, but these impediments are not insurmountable.

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