**MINISTERUL EDUCAŢIEI NAŢIONALE**
**UNIVERSITATEA TEHNICĂ DE CONSTRUCŢII BUCUREŞTI**

# Ph.D. Thesis

# -Summary-

# Modern methods of base isolation in the Romanian seismic zone

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## Abstract

The seismic response of base-isolated structures can be effectively estimated with the equivalent lateral force procedure, which produces consistent results that reflect the nonlinear properties of the isolation system. This paper describes a new approach in applying the equivalent lateral force procedure to evaluate the seismic response of base-isolated structures. The first step of the method is to directly target the level of reduction of the base shear forces and assume the effective damping of the isolation system. With this input, the normalized elastic response spectrum, the effective period and the elastic displacement response spectrum can be directly determined. In the next step, the effective lateral stiffness of the isolation system is determined. In the final stage, the isolation system's material and geometrical properties are determined to obtain the assumed effective damping and stiffness. The general procedure is implemented to the European norms and the mathematical formulas are derived. As an example, the procedure is applied for a structure in Bucharest, situated in the Vrancea seismic zone.

The concrete frame structures are designed for full isolation, with the equivalent behavior reduction factor equal to the behavior reduction factor of the base fixed structure (6.75). In order to capture different seismic inputs, several analysis are made for different upper limits of the period of the constant spectral acceleration branch (0.7s, 1.0s and 1.6s) and different values for the design ground acceleration (0.2g, 0.3g and 0.4g). These analysis show that, for high upper limits of the period of the constant spectral acceleration branch and high design ground accelerations, the elastomeric bearings are not an effective method to obtain full isolation.


Index Terms— base-isolated structures, effective damping and stiffness, equivalent lateral force procedure, seismic design.

# 1. Seismic response of base isolated structures using equivalent lateral force procedure

This chapter presents a new approach in applying the equivalent lateral force procedure to evaluate the seismic response of base-isolated structures. The classic approach to the equivalent lateral force procedure is to design to maximum displacement in an iterative process. In the proposed approach the aim is to design to a maximum base shear reduction factor at the imposed targeted effective damping. This approach leads to a straightforward design and a better understanding and control of the isolation system.

The accelerated development in production capabilities of isolation systems and recent studies offer better control and understanding of the design of the base isolation systems and methods. In the proposed approach, the aim is to design to a maximum base shear reduction factor and then target the effective damping, based on engineering reasoning. The design procedure follows the next steps:

**Step-1. Determine the site-specific response spectra curves for the base fixed structure.**

The code specifications generally provide a representation of the spectral acceleration as a function of period:

$$S_e(T)_{5\%} = D_D^* D_D \cdot g \quad (1)$$

Where *C(T)* is a base shear coefficient as a function of period, and *g* is the gravitational acceleration. In Fig. 1.1 $T_1^{bf}$ is the fundamental period of the fixed base structure and $C(T_1^{bf})$ is the spectral acceleration ordinate for the fixed base structure.

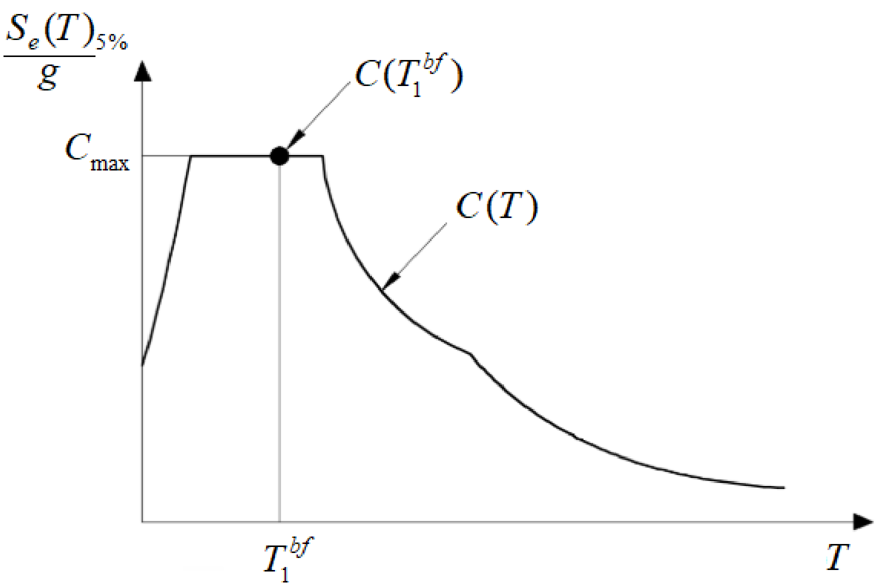



**Fig. 1.1 Response spectra curves**

**Step-2. Assume a target maximum base shear reduction factor depending on the structural system.**

The maximum base shear reduction factor represents the starting point of the design. Fixed-base structures are designed according to the capacity design principle. Capacity design is a design process that reduces the lateral seismic forces applied to a structure by accepting damage to structural components that are permitted to yield. Depending on the structural system type, redundancy and ductility, different levels of reduction may be applied. The reductions are introduced in the European codes as the behavior factor "*q*" and in the American codes as the reduction factor "R".

Base isolation takes the opposite approach and reduces the seismic response of the structure, rather than increasing the capacity. For optimal base isolation, the level of reduction of the lateral seismic forces is strictly connected to the type of structure, flexibility, redundancy and ductility. For full isolation, the equivalent behavior reduction factor should be equal to the behavior reduction factor of the base fixed structure.

The maximum base shear reduction gives a clear optimal necessary level of base isolation for an economically and dynamically efficient design. We define $q_{equiv}$ or $R_{equiv}$ as an equivalent behavior reduction factor, which expresses the reduction of the lateral seismic forces and is given by:

$$R_{equiv} = \frac{R^{bf}}{R^{bi}} \xleftrightarrow{or} q_{equiv} = \frac{q^{bf}}{q^{bi}} \tag{2}$$

Where: $R^{bf}$ or $q^{bf}$ is the reduction or behavior factor for the fixed structure and $R^{bi}$ or $q^{bi}$ is the reduction or behavior factor for the isolated structure ($q^{bi} \leq 1.5$ in the European codes and $R^{bi} = 3/8R^{bf} < 2$ in the American codes.

**Step-3. Assume the targeted effective damping and the reduction factor of the spectral acceleration based on the site-specific response spectra curves.**

The principle of isolation systems aims to redirect the seismic energy (period shift effect), rather than absorb it through damping. Recent studies, such as the one by Lee JJ and Kelly JM (2019) [5], demonstrate that the presence of a high damping ratio in the isolation system excites the higher modes thus counteracts the objective of base isolating a structure. In conclusion, the increase in damping leads to a more unstable dynamic response of the excitation of response in higher modes.

Furthermore, Kelly TE (2001) states that at DBE levels of earthquake, damping of 15% to 20% can generally be achieved, while in high seismic zones, the damping at MCE levels of load will often not exceed 10% to 12%.

Moreover, the accelerated development in production capabilities and material properties of isolation systems offer the liberty for the structural engineer to dimension the isolation system to target the assumed damping coefficient.

In these conditions, the structural engineer can assume the targeted effective damping based on the site-specific response spectra curves.

In the next three steps the spectral acceleration, the effective period and the effective displacement of the base isolated structure can be evaluated. These values depend only on the elastic response spectra curves, effective damping and the equivalent behavior reduction factor.

**Step-4. Calculate the effective spectral acceleration at the target maximum base shear reduction factor.**

The effective spectral acceleration $S_e(T_{eff}^{bi})_{5\%}$ (Fig. 5) can be expressed with:

$$S_e(T_{eff}^{bi})_{5\%} = \frac{C(T_1^{bf})}{q_{equiv}\eta_{eff}^{bi}} \xleftrightarrow{or} \frac{C(T_1^{bf})}{R_{equiv}B_{eff}^{bi}} \tag{3}$$

Where $T_{eff}^{bi}$ is the effective period of the base isolated structure at the target maximum base shear reduction factor and $\eta_{eff}^{bi}$ is the damping correction factor of the isolation system ($B_{eff}^{bi}$ in the American standards).

**Step-5. Calculate the effective period at the target maximum base shear reduction factor.**

Next, the elastic response spectrum function can be inverted to obtain the effective period for the base isolated structure (Fig. 1.2).

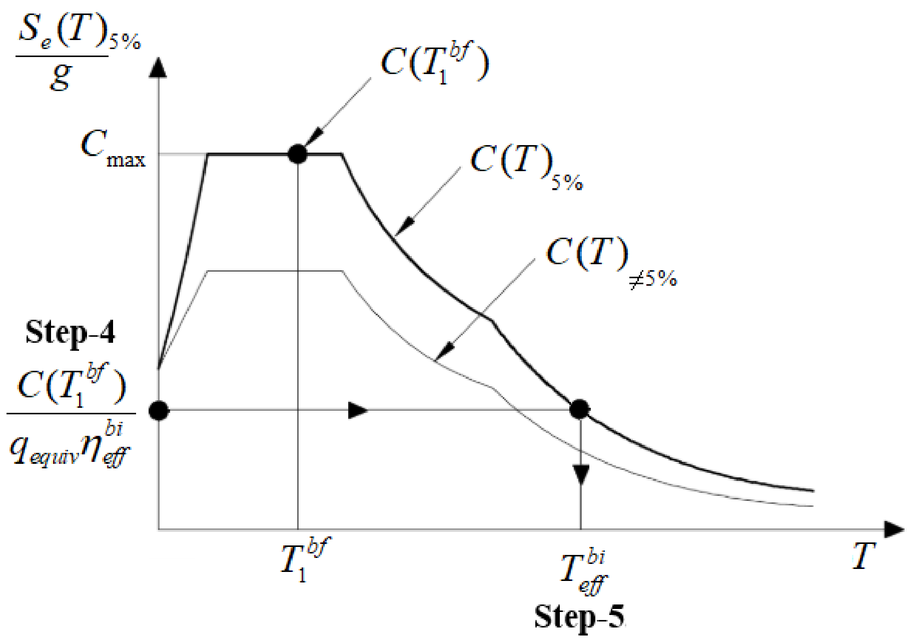



**Fig. 1.2 Determination of the effective spectral acceleration and effective period**

**Step-6. Calculate the effective displacement at the target maximum base shear reduction factor.**

The effective displacement of an isolated structure can be expressed as:

$$d_{dc}^{bi} = S_e(T_{eff}^{bi})_{\xi=5\%} \cdot \eta_{eff}^{bi} \cdot \left(\frac{T_{eff}^{bi}}{2\pi}\right)^2 \qquad (4)$$

The expressions of the effective spectral acceleration, period and displacement can be derived for any seismic design code and any elastic response spectra curve.

**Step-7. Determine the effective stiffness (normalized by the building weight) and dimension the isolation system using the code-imposed safety factors.**

$$K_{eff}^{bi} = M \cdot \left(\frac{T_{eff}^{bi}}{2\pi}\right)^2 \qquad (5)$$

**Step-8. Check if the yielding force of the isolation system is smaller than the seismic base shear force for the isolated structure.**

**Step-9. Dimension the superstructure and infrastructure of the base-isolated building using the code-imposed safety factors.**

The flowchart of the current approach of the equivalent lateral force procedure is presented in Fig. 1.3.

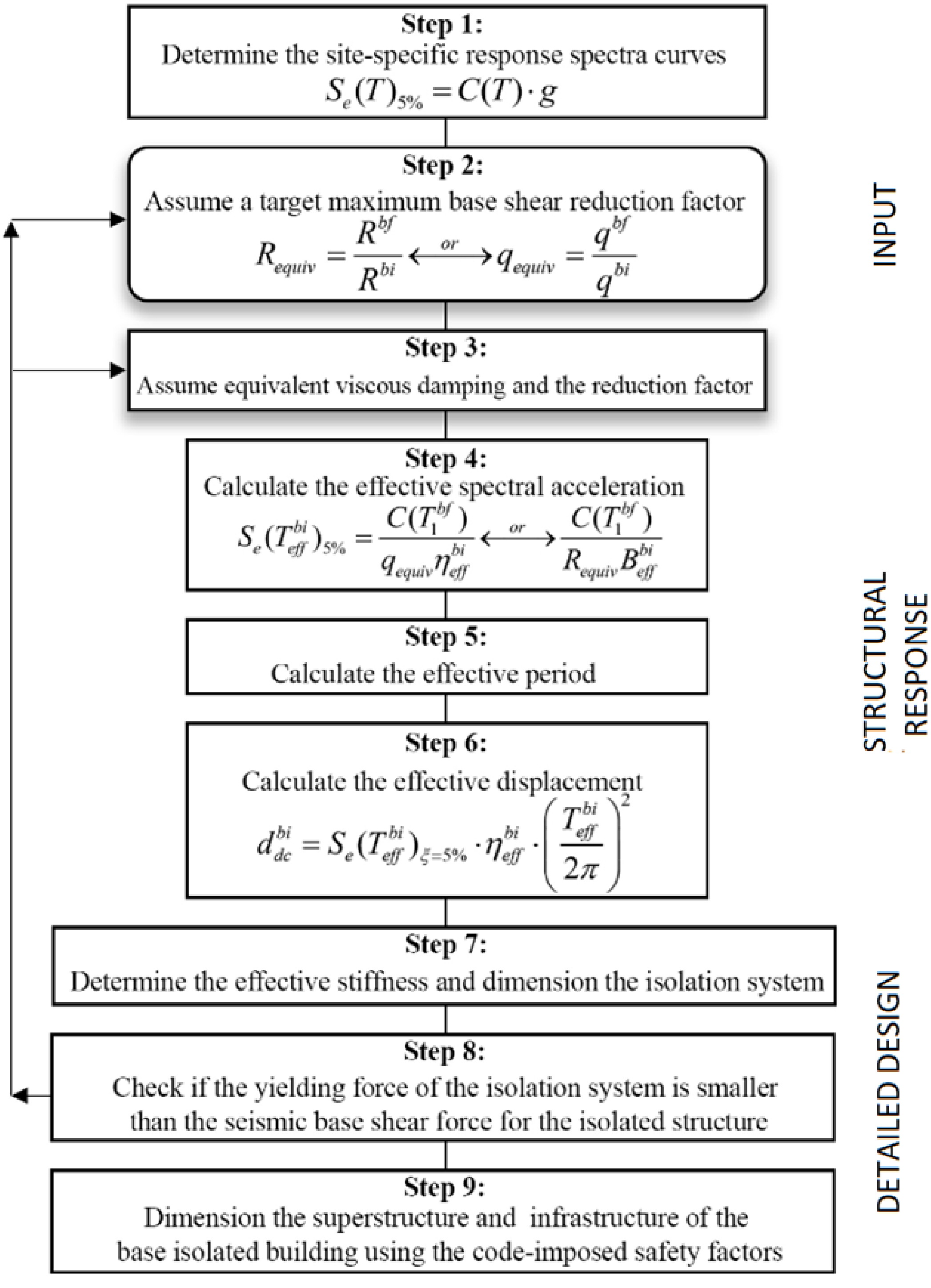



**Fig.** 1.**3 Flowchart of the proposed ELF procedure**

## Case Study: Implementation Of The Method On Eurocode 8

To emphasize the method, the principles will be applied to the design code: "EN 1998-1:2004, Eurocode 8: Design of structures for earthquake resistance". The design procedure is now applied:

***1. INPUT:***

**Step-1. Determine the site-specific response spectra curves for the base fixed structure.**

In EN 1998 the earthquake motion is represented as an elastic ground acceleration response spectrum, with the same shape for both the ultimate limit state and the serviceability limit state (Fig. 1.4).

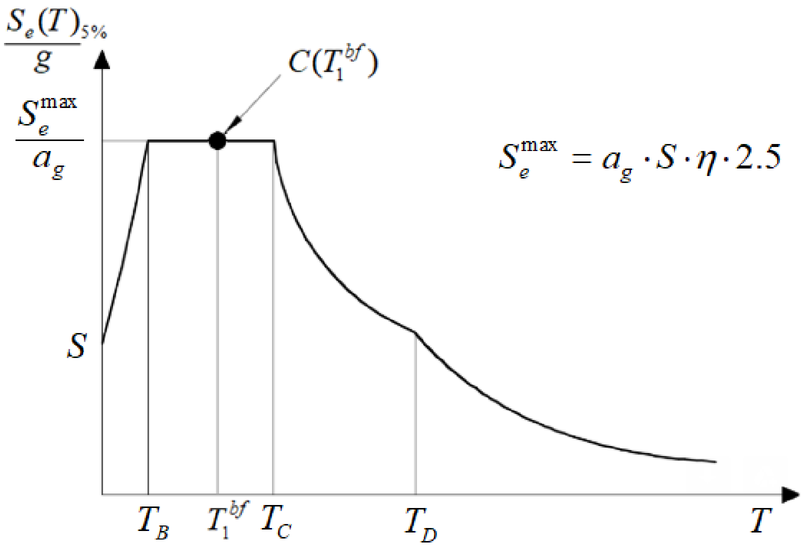



**Fig. 1.4 Shape of the elastic response spectrum**

The elastic response spectrum for the horizontal components $S_e(T)$ at the fundamental period of the base fixed structure is defined by:

$$\begin{aligned} T_B < T < T_C &\longrightarrow S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \\ T_C < T < T_D &\longrightarrow S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \frac{T_C}{T} \\ T_D < T < 4s &\longrightarrow S_e(T) = a_g \cdot S \cdot \eta \cdot 2.5 \cdot \frac{T_C \cdot T_D}{T^2} \end{aligned} \quad (6)$$

Where: $T$ is the fundamental period of the building, $a_g$ is the design ground acceleration ( $a_g = \gamma_I \cdot a_{gR}$), $T_B$ is the lower limit of the period of the constant spectral acceleration branch, $T_C$ is the upper limit of the period of the constant spectral acceleration branch, $T_D$ is the value defining the beginning of the constant displacement response range of the spectrum, $S$ is the soil factor, and $\eta$ is the damping correction factor, expressed by the following relation:

$$\eta = \sqrt{10/(5+\xi)} \geq 0.55 \qquad (7)$$

Where $\xi$ is the viscous damping, with the reference at 5% ($\eta_{5\%}$ =1).

For a base fixed structure, with the fundamental period $T_1^{bf}$ , (6) can be reduced to:

$$S_e(T_1^{bf}) = S_e^{\max} \cdot C_{T_1^{bf}} \qquad (8)$$

Where:

$$S_e^{\max} = a_g \cdot S \cdot \eta \cdot 2.5 \qquad (9)$$

And $C_{T_1^{bf}}$ is a constant depending on the fundamental period of the base fixed structure:

$$\begin{aligned} &T_B < T_1^{bf} < T_C \longrightarrow C_{T_1^{bf}} = 1 \\ &T_C < T_1^{bf} < T_D \longrightarrow C_{T_1^{bf}} = \frac{T_C}{T_1^{bf}} \\ &T_D < T_1^{bf} < 4s \longrightarrow C_{T_1^{bf}} = \frac{T_C \cdot T_D}{(T_1^{bf})^2} \end{aligned} \qquad (10)$$

**Step-2. Assume a target maximum base shear reduction factor depending on the structural system.**

In the first stage of the design the structure is considered with the base fixed. The base shear force $F_b^{bf}$ can be calculated with the following expression:

$$F_b^{bf} = S_d(T_1^{bf}) \cdot m \cdot \lambda^{bf} \qquad (11)$$

Where: $T_1^{bf}$ is the fundamental period of the building, $\lambda^{bf}$ is the correction factor and is equal to 0.85 if $T_1 < 2\ T_C$ and the building has more than two stories, or 1.0 otherwise, and:

$$S_d(T_1^{bf}) = S_e(T_1^{bf}) / q^{bf} \qquad (12)$$

Where: $q^{bf}$ is the behavior factor of the structure

In the next stage of the design the structure is considered with a seismic isolated base. We define $q_{equiv}^{\max}$ as an equivalent behavior factor, which expresses the reduction of the lateral seismic forces and is given by:

$$q_{equiv}^{\max} = \frac{q^{bf} \cdot \lambda^{bf}}{q^{bi} \cdot \lambda^{bi}} \qquad (13)$$

Where: $q^{bi}$ is the behavior factor of the structure with the isolated base (maximum 1.5 according to Eurocode 8) and $\lambda^{bi}$ is the correction factor for the base-isolated structure.

**Step-3. Assume the targeted effective damping and the reduction factor of the spectral acceleration based on the site-specific response spectra curves.**

***2. STRUCTURAL RESPONSE:***

**Step-4. Calculate the effective spectral acceleration at the target maximum base shear reduction factor.**

The targeted effective spectral acceleration can be expressed as the ratio between the elastic response spectrum for the horizontal components at the fundamental period of the base fixed structure and the maximum equivalent behavior factor:

$$S_e(T_{eff}^{bi}, \xi_{eff\,eff}^{bi})_{\xi \neq 5\%} = \frac{S_e(T_1^{bf})_{\xi=5\%}}{q_{equiv}^{\max}} \qquad (14)$$

Applying the spectral conversion, the final relation can be obtained:

$$S_e(T_{eff}^{bi}, \xi_{eff\,eff}^{bi})_{\xi=5\%} = \frac{S_e^{\max} \cdot C_{T_1^{bf}}}{q_{equiv}^{\max} \cdot \eta_{eff}^{bi}} \qquad (15)$$

Where $\eta_{eff}^{bi}$ is the damping correction factor for the effective damping $\xi_{eff}^{bi}$ of the isolation system.

Considering that base isolation is most economically and technically feasible for $T_B < T_1^{bf} < T_C$, the effective spectral acceleration becomes:

$$S_e(T_{eff}^{bi}, \xi_{eff\,eff}^{bi})_{\xi=5\%} = \frac{S_e^{\max}}{q_{equiv}^{\max} \cdot \eta_{eff}^{bi}} \qquad (16)$$

**Step-5. Calculate the effective period at the target maximum base shear reduction factor.**

Next, the elastic response spectrum functions (10) are inversed to obtain the effective period for a base isolated structure.

We define $S_e(T_D)$:

$$S_e(T_D) = S_e^{\max} \cdot \frac{T_C}{T_D} \qquad (17)$$

For the base-isolated structure, we may encounter two situations:

1. If: $S_e(T_{eff}^{bi}, \xi_{eff\,eff}^{bi})_{\xi=5\%} > S_e(T_D)$

$$S_e(T_{eff}^{bi}, \xi_{eff\,eff}^{bi})_{\xi=5\%} = S_e^{\max} \cdot \frac{T_C}{T_{eff}^{bi}} \qquad (18)$$

Substituting (15), the effective period at the target maximum base shear reduction factor is:

$$T_{eff}^{bi} = q_{equiv}^{\max} \cdot \eta_{eff}^{bi} \cdot T_C / C_{T_1^{bf}} \tag{19}$$

2. If: $S_e(T_{eff}^{bi}, \xi_{eff\,eff}^{bi})_{\xi=5\%} < S_e(T_D)$

$$S_e(T_{eff}^{bi}, \xi_{eff\,eff}^{bi})_{\xi=5\%} = S_e^{\max} \cdot \frac{T_C \cdot T_D}{(T_{eff}^{bi})^2} \tag{20}$$

Substituting (15), the effective period at the target maximum base shear reduction factor is:

$$T_{eff}^{bi} = \sqrt{q_{equiv}^{\max} \cdot \eta_{eff}^{bi} \cdot T_C \cdot T_D / C_{T_1^{bf}}} \tag{21}$$

**Step-6. Calculate the effective displacement at the target maximum base shear reduction factor.**

The effective displacement of an isolated structure, accordingly to the ELF procedure, can be expressed as:

$$d_{dc}^{bi} = S_e(T_{eff}^{bi}, \xi_{eff}^{bi})_{\xi\neq5\%} \cdot \left(\frac{T_{eff}^{bi}}{2\pi}\right)^2 \tag{22}$$

Applying the damping correction factor (“damping effect”):

$$d_{dc}^{bi} = S_e(T_{eff}^{bi}, \xi_{eff}^{bi})_{\xi=5\%} \cdot \eta_{eff}^{bi} \cdot \left(\frac{T_{eff}^{bi}}{2\pi}\right)^2 \tag{23}$$

For the base-isolated structure, we encounter two situations:

1. If: $S_e(T_{eff}^{bi}, \xi_{eff}^{bi})_{\xi=5\%} > S_e(T_D)$

$$d_{dc}^{bi} = S_e^{\max} \cdot \frac{T_C}{T_{eff}^{bi}} \cdot \eta_{eff}^{bi} \cdot \left(\frac{T_{eff}^{bi}}{2\pi}\right)^2 \tag{24}$$

Substituting (19), the effective period at the target maximum base shear reduction factor is:

$$d_{dc}^{bi} = q_{equiv}^{\max} \cdot (\eta_{eff}^{bi})^2 \cdot \frac{S_e^{\max} \cdot T_C^2}{4\pi^2} \tag{25}$$

2. If: $S_e(T_{eff}^{bi}, \xi_{eff}^{bi})_{\xi=5\%} < S_e(T_D)$

$$d_{dc}^{bi} = S_e^{\max} \cdot \frac{T_C \cdot T_D}{(T_{eff}^{bi})^2} \cdot \eta_{eff}^{bi} \cdot \left(\frac{T_{eff}^{bi}}{2\pi}\right)^2 \tag{26}$$

The effective period at the target maximum base shear reduction factor is:

$$d_{dc}^{bi} = \eta_{eff}^{bi} \cdot \frac{S_e^{\max} \cdot T_C \cdot T_D}{4\pi^2 \cdot C_{T_1^{bf}}} \qquad (27)$$

### *3. DETAILED DESIGN:*

**Step-7. Determine the effective stiffness (normalized by the building weight) and dimension the isolation system using the code-imposed safety factors.**

The effective stiffness is:

$$K_{eff}^{bi} = M \cdot \left( \frac{2\pi}{T_{eff}^{bi}} \right)^2 \qquad (28)$$

Where $T_{eff}^{bi}$ was determined by (19) or (21) and $M$ is the total mass of the building. With the values of the effective stiffness and damping, the isolation system can be designed. The geometry and materials properties will be designed to obtain the effective stiffness and damping assumed in the general design of the isolated structure.

**Step-8. Check if the yielding force of the isolation system is smaller than the seismic base shear force for the isolated structure.**

**Step-9. Dimension the superstructure and infrastructure of the base-isolated building using the code-imposed safety factors.**

## Conclusions

This research describes a new approach in applying the equivalent lateral force procedure to evaluate the seismic response of base isolated structures. Designing to a maximum base shear reduction factor at a targeted effective damping leads to a clear optimal necessary level of base isolation for an economically and dynamically efficient design.

The general procedure is implemented to the European norms and the mathematical formulas are derived. The numerical example of a base-isolated structure design underlines the utility of the method as a preliminary design. After the preliminary design, successful implementation of base isolation instead of the basic solution requires further complex analysis. The structural engineer has to generally consider procurement strategies, construction particularities, manufacturing capabilities, analyze the optimum type of isolator based on their properties, select the optimum material properties, analyze the savings in structural system costs and reduced damage cost.

# 2. Evaluation of the efficiency of base isolation systems for concrete frame and shear wall structures

## 2.1. Introduction

This research evaluates through numerical methods the efficiency of friction pendulum bearings and elastomeric bearings for base isolated concrete frame and shear wall structures. The seismic response of base isolated structures can be effectively estimated with the equivalent lateral force procedure, which produces consistent results that reflect the nonlinear properties of the isolation systems.

The concrete frame structures are designed for full isolation, with the equivalent behavior reduction factor equal to the behavior reduction factor of the base fixed structure (6.75). The concrete wall structures are designed for full isolation, with the equivalent behavior reduction factor equal to the behavior reduction factor of the base fixed structure (4.6).

In order to capture different seismic inputs, several analysis are made for different upper limits of the period of the constant spectral acceleration branch (0.7s, 1.0s and 1.6s) and different values for the design ground acceleration (0.2g, 0.3g and 0.4g). These analysis show that, for high upper limits of the period of the constant spectral acceleration branch and high design ground accelerations, the elastomeric bearings are not an effective method to obtain full isolation.

## 2.2. Problem description and analysis objectives

This research evaluates the efficiency of friction pendulum bearings and elastomeric bearings for base isolated structures. The most suitable structures are those with short natural period, less then approximately 1 second [6].

For the flexible concrete frames structural system, this translates to a maximum of 5-6 stories. For the analysis there were considered 3 concrete frame structures with different heights (GF+2S, GF+4S and GF+6E) in order to capture the different behavior caused by the flexibility of the building. All structures have the same double symmetrical floor plan with 4 spans of 6m each (Fig. 2.1). The gravitational forces are transferred through a 15cm thick concrete slab. The story height is 3m.

For the relatively flexible concrete wall structural system, this translates to a maximum of 9-10 stories. For the analysis there were considered 3 concrete wall structures with different heights (GF+6F, GF+8F and GF+10F) in order to capture the different behavior caused by the flexibility of the building. All structures have the same double symmetrical floor plan with 4 spans of 6m each (Fig. 2.1). The gravitational forces are transferred through a 15cm thick concrete slab. The story height is 3m

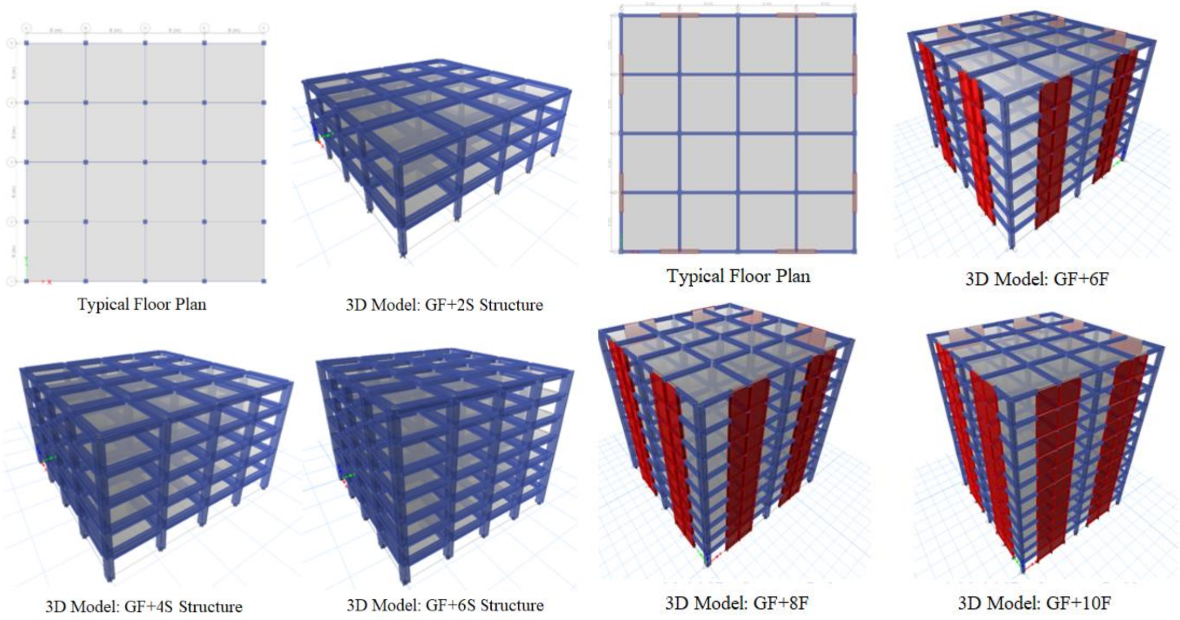
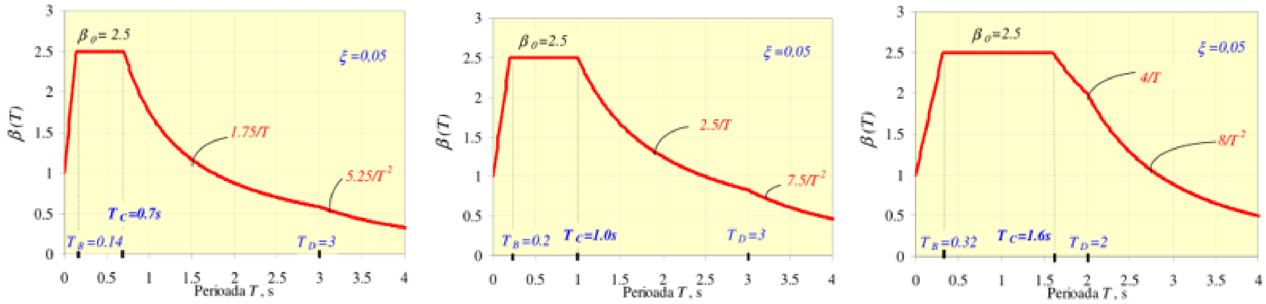



**Fig. 2.1 Structural models**

In order to capture different seismic inputs, several analysis are made for different upper limits of the period of the constant spectral acceleration branch (0.7s, 1.0s and 1.6s) and different values for the design ground acceleration (0.2g, 0.3g and 0.4g). These leads to a total of 27 wall structures, 9 for each different height. The site-specific response spectra curves (Vrancea seismic region (7)) are presented in Fig. 2.2.




| | | |
|---|---|---|
| $T_C$ | 0.7 | s |
| $T_D$ | 3.0 | s |
| $C_1$ | 1.75 | - |
| $C_2$ | 5.25 | - |
| $\beta_D$ | 0.583 | - |

| | | |
|---|---|---|
| $T_C$(s) | 1.0 | s |
| $T_D$ | 3.0 | s |
| $C_1$ | 2.50 | - |
| $C_2$ | 7.50 | - |
| $\beta_D$ | 0.833 | - |

| | | |
|---|---|---|
| $T_C$(s) | 1.6 | s |
| $T_D$ | 2.0 | s |
| $C_1$ | 4.00 | - |
| $C_2$ | 8.00 | - |
| $\beta_D$ | 2 | - |

**Fig. 2.2 Seismic input**

In the first stage of the analysis the structures were dimensioned considering to be fixed based. The design was done using the equivalent lateral force procedure, according to „Eurocode 8: Design of structures for earthquake resistance, Part 1: General rules, seismic actions and rules for buildings”, in order to meet the lateral displacements requirements.

The equivalent lateral force procedure is a displacement-based method that considers two horizontal dynamic translations and superimposes static torsional effects. It assumes that the superstructure is a rigid solid translating above the isolation system [1], [2], [3].

In the next stage of the design the structures were considered base isolated. For each seismic scenario, the following base isolation system is dimensioned:

1. Low damping rubber bearing (LDRB)
2. Lead rubber bearings (LRB)
3. High damping rubber bearings (HDRB)
4. Friction pendulum bearings (FP)
5. Double concave friction pendulum bearings (DCFP)
6. Triple concave friction pendulum bearings (TCFP)

The key parameters that capture the nonlinear behavior are the effective damping ($\xi_{eff}$ in the European design codes or $\beta_{eff}$ in the American design codes) and the effective stiffness ($K_{eff}$). For all the analysis it was considered 20% damping for the high damping rubber bearings (HDRB) and 30% damping for the other base isolation systems.

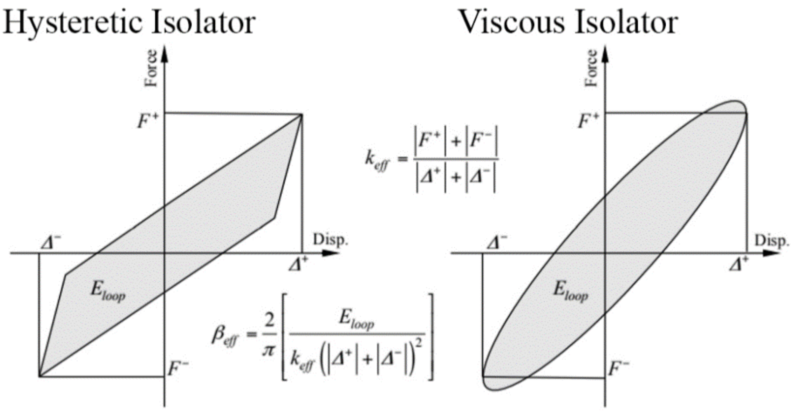



**Fig. 2.3 Effective stiffness and effective damping [2]**

## 2.3. Results for elastomeric bearings

The analysis show that, for high upper limits of the period of the constant spectral acceleration branch and high design ground accelerations, the elastomeric bearings are not an effective method to obtain full isolation.

For high upper limits of the period of the constant spectral acceleration branch and high design ground accelerations the elastomeric bearings have problems with the lateral stability at large displacements demands. Therefor, a critical design restriction is the critical axial load *W* at the maximum displacement demand. The main factor that influences the lateral stability is the reduced area $A_r$, which is define as the overlapping area of the inferior undeformed surface and the superior deformed surface of the elastomeric bearing as presented in Fig. 2.4.

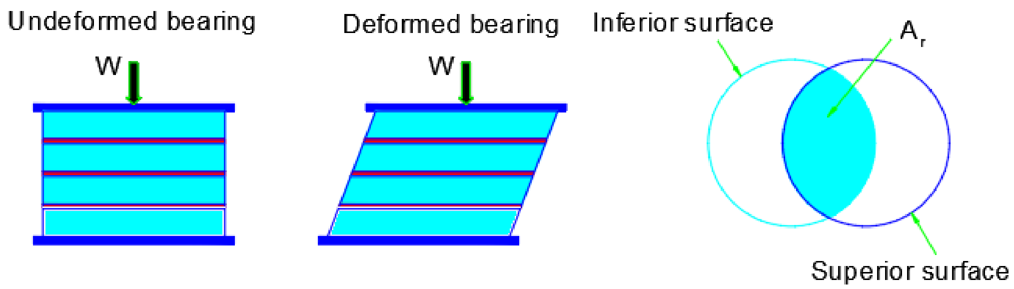



**Fig. 2.4 Stability at large displacements**

At step 6 of the equivalent lateral force procedure it is determined the effective displacement at the target maximum base shear reduction factor. For the design of the elastomeric bearings, the lateral stability check is made before proceeding to the detailed design. In the case that the elastomeric bearing does not fulfill the stability check, it is determined the maximum admissible displacement for which the stability checks. The design continues accordingly to the proposed equivalent lateral force procedure.

In Fig. 2.5 and Fig. 2.6 there are presented the effective spectral accelerations obtained for the elastomeric bearings. It can be concluded that:

- For the period of the constant spectral acceleration branch of 0.7s full base isolation can be achieved.
- For the period of the constant spectral acceleration branch of 1.0s only a moderate base isolation can be achieved.
- For the period of the constant spectral acceleration branch of 1.6s little base isolation can be achieved.

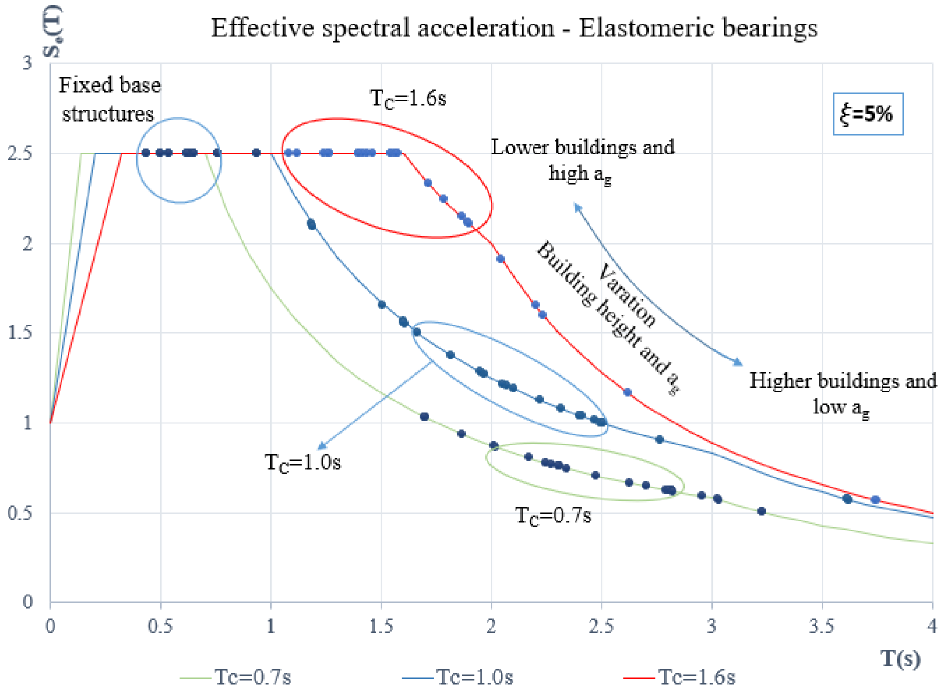



**Fig. 2.5 Frame structures - Effective spectral acceleration – Elastomeric bearings**

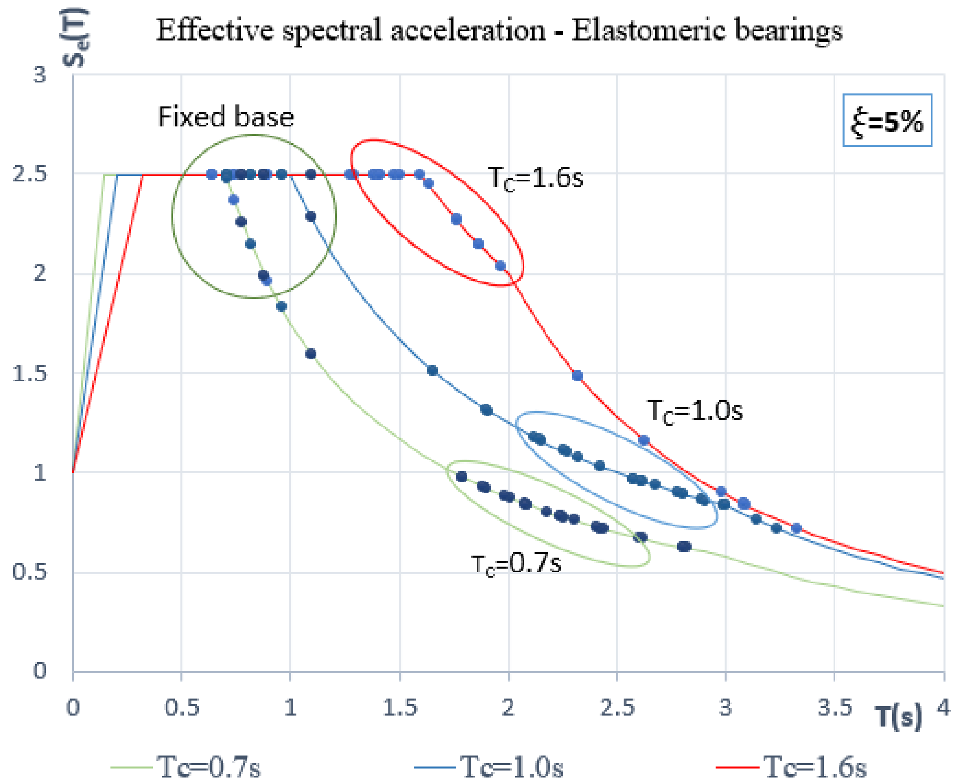



**Fig. 2.6 Wall structures - Effective spectral acceleration – Elastomeric bearings**

## 2.4. Results for friction pendulum bearings

The friction pendulum bearings can be successfully applied to all site locations and seismic inputs. In Fig. 2.7 and Fig. 2.8 there are presented the effective spectral accelerations obtained for the friction pendulum bearings. Although it was considered a high level of seismic base isolation (all three friction pendulum systems achieve full isolation.

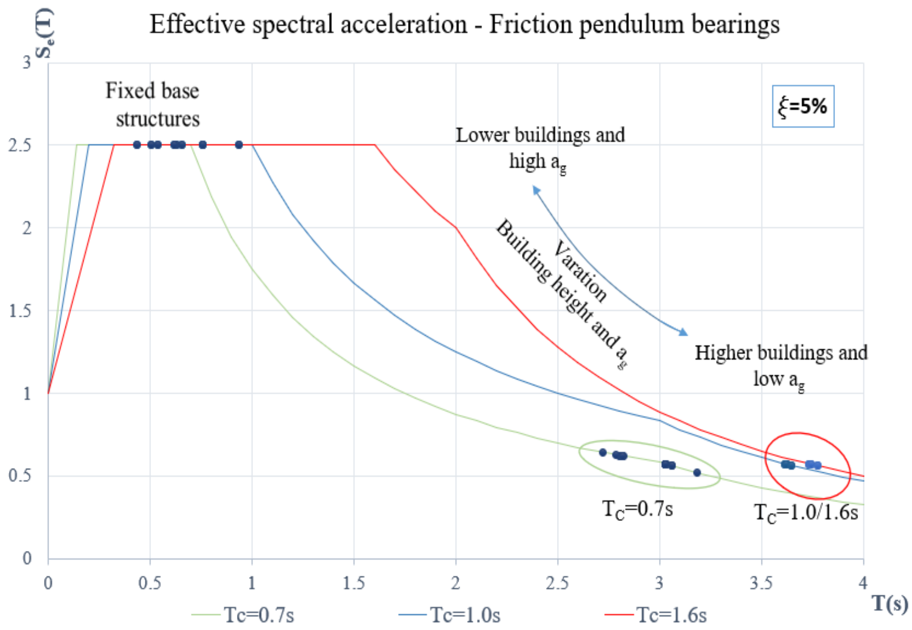



**Fig. 2.7 Frame structures - Effective spectral acceleration – Friction pendulum bearings**

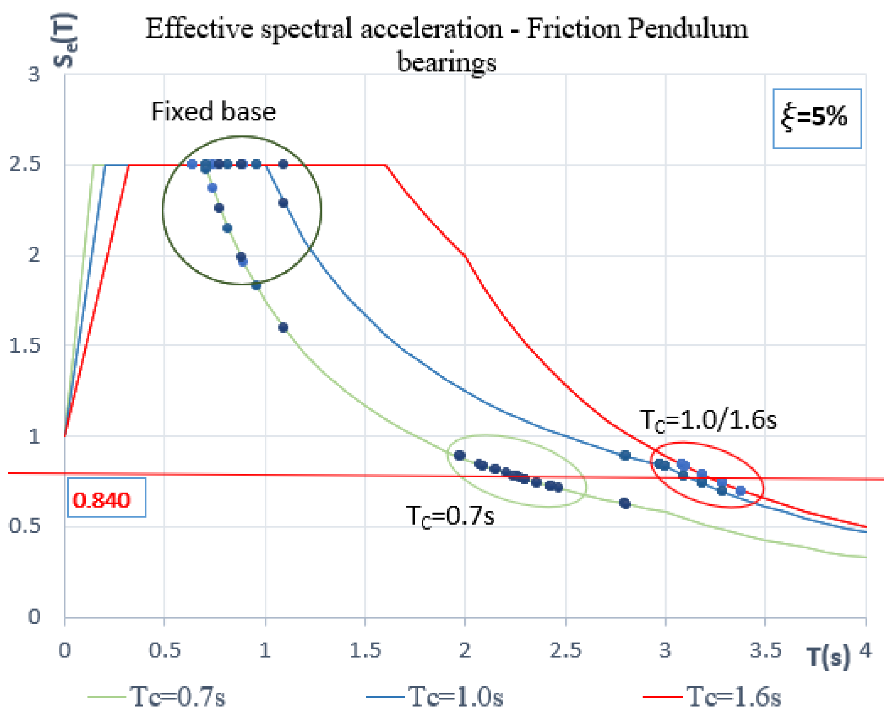



**Fig. 2.8 Wall structures - Effective spectral acceleration – Friction pendulum bearings**

## 2.5. Discussions And Conclusions

This paper evaluates through numerical methods the efficiency of friction pendulum bearings and elastomeric bearings for base isolated structures.

The structures are designed for full isolation, with the equivalent behavior reduction factor equal to the behavior reduction factor of the base fixed structure.

The seismic response of the base isolated structures is obtained using the equivalent lateral force procedure. Designing to a maximum base shear reduction factor at a targeted effective damping leads to a clear optimal necessary level of base isolation for an economically and dynamically efficient design.

In order to capture different seismic inputs, several analysis are made for different upper limits of the period of the constant spectral acceleration branch (0.7s, 1.0s and 1.6s) and different values for the design ground acceleration (0.2g, 0.3g and 0.4g). These analysis show that, for high upper limits of the period of the constant spectral acceleration branch and high design ground accelerations, the elastomeric bearings are not an effective method to obtain full isolation.

After the preliminary design, successful implementation of base isolation instead of the basic solution requires further complex analysis.

The structural engineer has to generally consider procurement strategies, construction particularities, manufacturing capabilities, analyze the optimum type of isolator based on their properties, select the optimum material properties, analyze the savings in structural system costs and reduced damage cost.

In Fig. 2.9 and Fig. 2.10 there is proposed, as a practical example of the results, a seismic zoning of Romania depending on the type of isolation system that can be used in order to achieve full isolation for concrete frames and wall structures (behavior factor=6.75/4.6 and 30% damping).

The proposed zoning is overlapped on the design ground accelerations map and on the period of the constant spectral acceleration branch map for Romania.

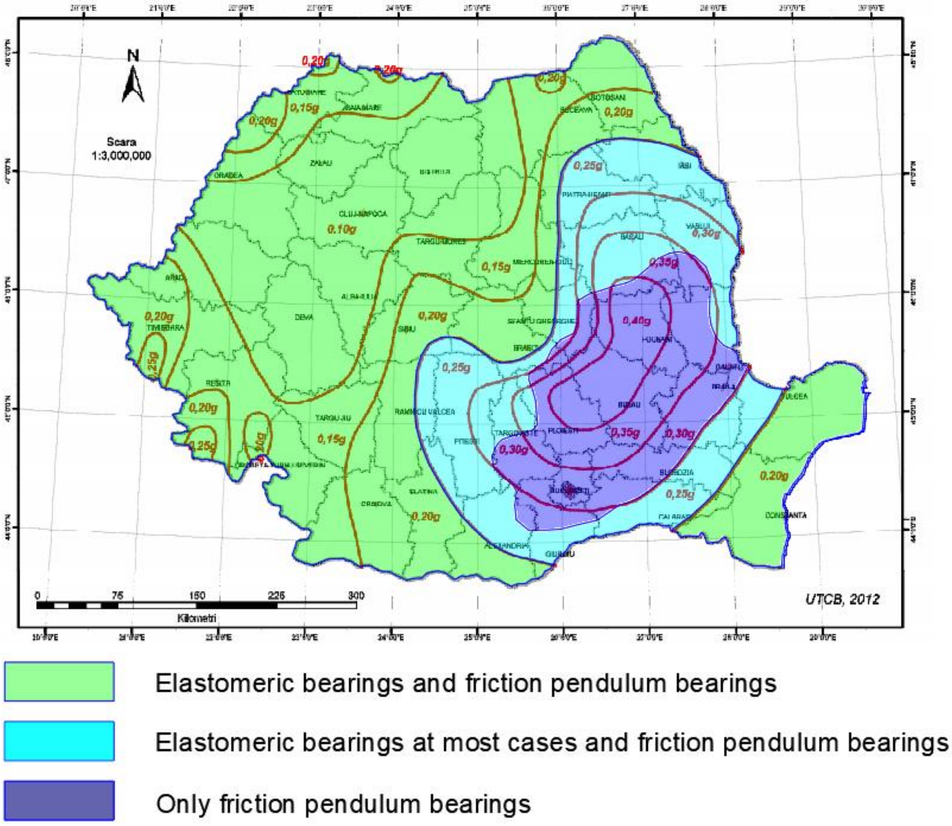



**Fig. 2.9 Design ground accelerations map for Romania- Zoning depending on the type of isolation systems**

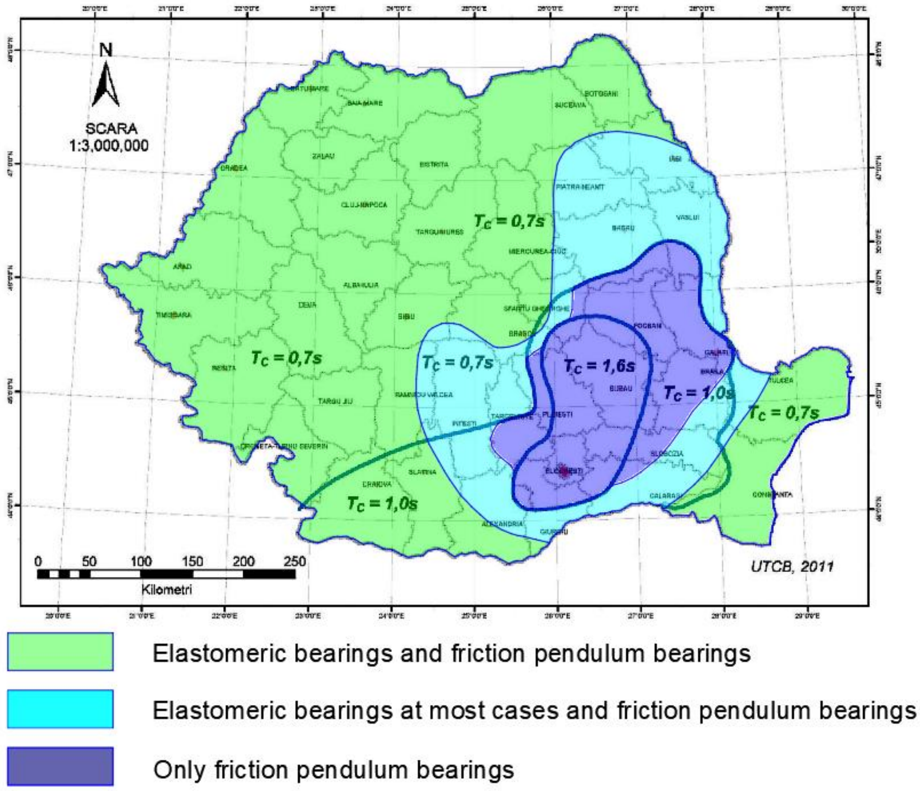



**Fig. 2.10 Period of the constant spectral acceleration branch map for Romania- Zoning depending on the type of isolation systems**

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