SEISMIC ISOLATION – EFFICIENT PROCEDURE FOR SEISMIC RESPONSE ASSESSEMENT

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ABSTRACT

The aim of this analysis is to reduce the dynamic response of a structure. The seismic isolation solution must take into consideration the specific site ground motion. In this paper will be presented results obtained by applying the seismic isolation method. Based on the obtained results, important conclusions can be outlined: the seismic isolation device has the ability to reduce seismic acceleration of the seismic isolated structure to values that no longer present a danger to people and environment; the seismic isolation solution is limiting devices deformations to safety values for ensuring structural integrity and stability of the entire system; the effective seismic energy dissipation and with no side effects both for the seismic isolated building and for the devices used, and the return to the initial position before earthquake occurrence are obtained with acceptable permanent displacement.

Key words: anti-seismic design, Vrancea earthquakes, seismic energy dissipation, seismic isolation

Introduction

The impact that a design earthquake has on a nuclear or non-nuclear objective depends on the characteristics of the seismicity of the site and the objective itself. Seismic isolation is the most effective way to protect structures against seismic events. The seismic isolation solution must take into account the specificities of onsite earthquakes, [8-9], a highly critical role having Vrancea earthquakes that, unlike the surface earthquakes, are slow earthquakes, with a corner period, T_C, moved to higher values. For this reason, the seismic isolation must be done using systems of isolating devices which are capable to overtake, without any risks, large displacements of the seismic response.

Seismic protection of structures

Efficient structural seismic protection must consider several issues that shall be further stated.

Seismic qualification

Currently, seismic qualification of non-nuclear objectives can be achieved by several methods, depending on the objective type: *very important* (heritage, museums, government targets, emergencies support, etc.), *seismic dynamic behavior* (high or short buildings, stiff or slender, etc.), *type of the site* (hard, average or soft soil), of the *earthquake type* (quick, moderate, and slow), of the *seismic qualification costs*, etc.

For nuclear objectives, until recently, it was used only the method that increased the rigidity of the structure's elements and the sectional loads were maintained into elastic domain. In the last years, they began to use other two methods for the seismic qualification, but only for modules/locations of the Nuclear Power Plants, that can provide sufficient guarantees that an accidental damage due to the site design earthquake exedance will not occur.

Base seismic isolation. Computer codes

The design codes studied in this paper, which uses the seismic isolation method, are*: (i) National Building Code: P100/2013,[3]; (ii) Eurocode 8; (iii) Japanese Design Code.* These codes can be applied to modules/substructures/systems of nuclear objectives which use seismic base isolation.

Mathematical models for describing hysteresis curves

This behavior is achieved using materials with high hysteretic dissipation on an oscillation cycle. The mathematical models studied in CITON are: *classical Bouc-Wen type, Taylor type, Maxwell type, Kevin-Voight type, Zener type, Ramberg-Osgood type, Bouc-Wen modified type, Bow type, Coulomb type.*

Seismic motion

Function of the analyzed objective (nuclear or non-nuclear), the seismic motion used for analyses must be according to the applicable guidelines: *CSA 289.3-10, [1]; AECL Design Guide CNE Cernavodă U1-U2, [2]; RIZZO & Assoc. for U3-U4 and CTRF, [4]; P100/2013, [3].*

Analysis method

The mathematical description, of the system made of structure and dampers, is, generally, a difficult activity and with a low accuracy, because: (i) the existing commercial computing programs on the market, cannot describe with sufficient accuracy the behavior of the most used damping devices (the nine types above mentioned). Those models, either are not mathematically implemented, either they have not a high degree of generality (narrow field for the parameters variation), either they cannot implement the specific hysteretic behavior (example: the case of strengthening/consolidation damping); (ii) modeling as realistic as possible the hysteretic behavior requires a real-time analysis for the accurate recoding of the energy dissipated by the loading – unloading cycles on the damping device.

Computational mathematical model

Mathematical model used for the seismic isolation process consist of: (1) structural model defined by the dynamic characteristics of the building; (2) computation mathematical model for dampers;

CITON Contribution

A representative as possible assessment of the seismic response of a building fitted with hysteretic devices or with isolation devices is achieved with Simulink application from Matlab. Simulink computing model development for more than 2 – 3 storeys it becomes a difficult task and it is exposed to high level of programming error. In order to prevent the occurrence of this type of errors, CITON has developed an automatic generation tool for seismic input for any number of usual storeys (maximum 20) requested by the object Differential Equation Editor in Simulink computing program.
This application becomes one of the computational tools necessary to performe analyses of seismic behavior of structures described in present methodology, [5-7]. This automatic generating tool for seismic input includes automatically of the nine types of hysteretic mathematical models.

Obtained results

In this paper were analyzed various possible cases of structures (building, equipment, platform, etc.) which will be actuated by an earthquake in the form of the design accelerogram. The results of applying the method for reducing seismic response were performed for the following cases:

1. Civil building

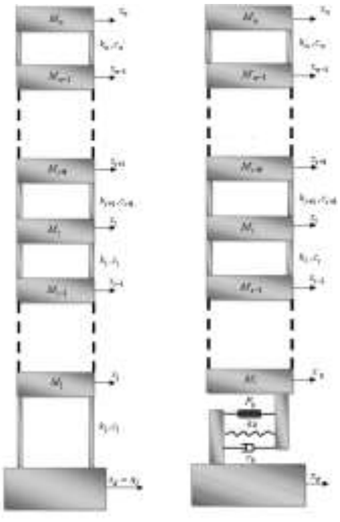
For an 8 – storey building placed in Cernavoda city the seismic isolation method was applied. The geometric design of the building is shown in Figure 1. The input data are according to P100/2013 National Building Code.

2. Structure belonging to a Nuclear Power Plant (NPP)

The case studied in point 1 can describe also, from the dynamic characteristics point of view, structures belonging to a NPP. The input data are according to [4].

3. Equipment, laboratory’s platform, Shaker’s platform, ventilation’s platform

The seismic response analysis of a structure, system or component (SSC) equipped with damping devices is made using the CTRF (Cernavoda Tritium Removal Facility) seismic analysis results, [10], because in this case we have the accelerograms for the building’s floor and for the attachments point of major SSCs. The seismic input data are floor accelerograms given by [4].



(a) Without DIS. *(b) With DIS*

Fig. 1. *Calculation model*

1. Civil building

It was considered an eight levels building, located in Cernavoda city, with a high level of horizontal and vertical symmetry. It has been hypothesized that the structure has a shear like dynamic behavior, considering that the floor has infinite stiffness in its plan. This way, nodal rotations is considered null.
Resistance of the structure is given by the columns and the stress is lateral shear. In this case, the structural rigidity is acting on horizontal direction. We also believe that the building has floors with equal masses and equal side rigidities. In order to determine the modal motion characteristics and the seismic response, it was considered, initially, the non-isolated building. For this type of structure, the first eagen vibration mode is approximately,$T_1 = 1s$ which coincides with the corner period from the ground response spectra of the analyzed site, [3]. Viscous damping ratio for module 1 is chosen,$\beta_1 = 5\%$. The structure is tested to a design accelerogram artificially generated and compatible with the design ground

response spectra, [3], and the dynamic response is calculated on the horizontal direction. The calculation of dynamic response is performed with Simulink application in Matlab, [5]. Table 1 shows the maximum values for relative displacement, drift, total accelerations and the seismic energy overtake by the non-isolated building.

Table 1. *Relative displacements, drift, total accelerations and the seismic energy overtake by the non-isolated building. Maximum values.*

Storey	Relative displacement [cm]	Drift displacement [cm]	Total acceleration [m/s^2]	Overtaken seismic energy
1	3.0	3.0	3.7	10.6
4	11.0	2.3	5.4	
8	16.0	0.6	7.0	

Building with isolation devices

The isolation devices placed have moisture free friction, C, and a classic Bouc-Wen hysteretic type. The equation of the hysteresis curves are shown in Figure 2. Both characteristics work simultaneously. The equation that describes the seismic motion with damping devices is:

$$M_0\ddot{x}_0 + F_H + \mu M_0 g \cdot sign(\dot{x}) = -M_0\ddot{u}_g$$

where hysteresis force, F_H is the solution of Bouc-Wen type differential equation. The building structure being cut at the base, it is not participating as stiffness and viscous damping to the dynamic behavior of the system. The conditions from previous section are maintained. In Figure 3 drift displacement, total acceleration variation and the hysteresis diagram for the system equipped with isolators are presented. Table 2 presents the maximum values for relative displacements, drift displacements, total acceleration and the seismic energy overtake by the isolated building. It appears that the presence of hysteretic dissipation reduces the relative deformation to approx. 11cm (from approx. 20 cm without hysteresis), reducing the peak-to-peak amplitude of 14 cm and a displacement from the equilibrium position at the end of approx. 6 cm due to the existence of friction. Also, the presence of friction will cause shocks absorption and accelerations reduction to approx. 0.08g, only accidentally to 0.1g (in few moments). Hysteretic diagrams obtained show that Bouc-Wen has the role to limit the deformations in isolation devices and Coulomb has the role to dissipate the seismic energy and eliminates shocks.

Table 2. *Relative displacement, drift, total acceleration and seismic energy overtake by isolation device (ID). Maximum values*

Level	Relative/drift displacement, [cm]	Total acceleration, [m/s^2]	Overtake seismic energy
ID	11.0	0.8	0.53

$$\frac{\dot{F}}{A - |F|^n(\beta + \gamma \cdot sign(F\dot{x}))} = \dot{x}$$

A, β, γ, n – hysteretic curve parameters;
F – hysteretic force; x – deformation;

$$F = \mu N \cdot sign(\dot{x})$$

μ, N – hysteretic curve parameters; $N = M_0 g$
F – hysteretic force; x – deformation;

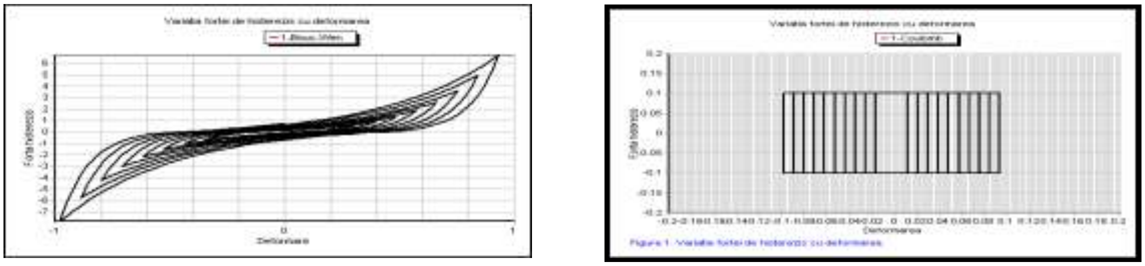


Fig. 2. *Schematic representation of the mathematical model SDOF with Isolation Device.*

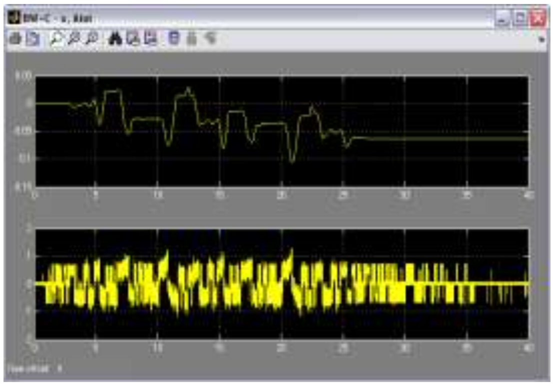


Fig. 3. Relative displacement and total displacement in isolation device *X_{max} = 11.0cm. A_{max} = 1.2m/s^2. A_{med} = 0.8m/s^2.*

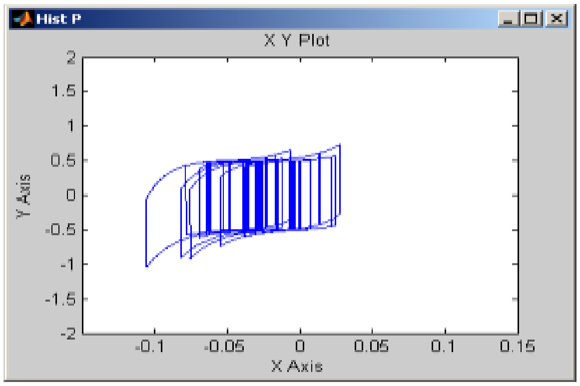


Fig. 7. Energy dissipated diagram in isolation device

2. Structures belonging to a NPP

Seismic isolation analysis of a building located in Cernavoda City (chapter "civil building") has been reviewed for the design earthquake DBE, in accordance with [4]. NPP structures are generally more rigid than civil ones, so that the results obtained are far-reaching because the seismic isolation of a more rigid structure is more effective. The requirement of seismic isolation philosophy is easier accomplished. Also, because DGRS RIZZO [4] has the maximum amplification level on a frequency range of approx. two times lower than in P100 / 2013, the use of a ID similar to that of a civil building is also more efficient, thus giving an extra ID's stability. The seismic action given by [4] represents the specific input data for U3 - U4 and CTRF building from Cernavoda NPP. Modal characteristics of the structure without isolation devices are those from chapter "Building without isolation devices". The period of the first vibration mode is approximately,$T_1 = 1s$ meaning that is farther than the$T_C \sim 0.4s$, from DGRS for the site analized, [4]. From this reason the building response, in relation to the one obtained in Chapter "Building without isolating devices" is lower (as amplification level), the structure having a self-isolation predisposition. Relative displacements, drift, total acceleration and seismic energy overtaken are given in Table 3.

Table 3. *Relative displacements, drift, total acceleration and seismic energy overtaken by the non-isolated building. Maximum values.*

Storey	Relative displacement [cm]	Drift [cm]	Total acceleration [m/s2]	Seismic energy overtaken
1	2.2	2.2	7.6	3.0
4	7.8	2.0	8.3	
8	12.2	0.9	10.0	

Seismic isolated building

Applying requirement (11.2) of [3], we choose the same isolating device with$T_0 = 3s$. Structure's response to the design accelerogram, [4], is showed in Figure 4. The presence of hysteretic dissipation reduces the relative deformation to approx. 20 cm, without residual deformation. The presence of friction will cause the shock absorption and the reduction of accelerations to approx. 0.12g, 0.22g accidentally in a few moments. Relative displacements, drift, total acceleration and seismic energy overtaken are given in Table 4.

From the comparison of the two cases result the following:

- Deformation in isolation device for NPP, x=20 cm, is higher than the one for Cernavoda city, x=11 cm, because the PGA values for the given accelerograms are 0.35g/0.2g=1.75. If were applied the same PGA for both cases, the device's deformation for NPP will be reduced to approximate 75%, meaning 11.4 cm, value practically identical with the one for the Cernavoda city.
- The total acceleration for NPP, A=0.12*g*, is higher than the one for Cernavoda city, A=0.08g. But, if we apply the same PGA, the total acceleration will be reduced to approximate 0.07g, value that is below the one for the city;
- The energy overtake by the isolator from earthquake is 2u, towards 0.53u and will reach a value of 0.65u if the same PGA were applied (the ratio is 3)

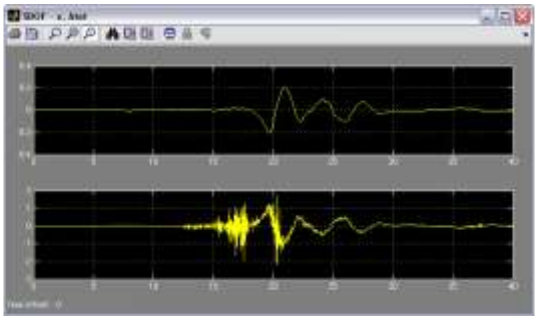


Fig. 4. Relative displacement and total acceleration in isolation. *X_{max} = 20.0cm. A_{max} = 2.2m/s^2. A_{med} = 1.2m/s^2.*

Table 4. Relative displacement, drift, total acceleration and seismic energy overtake by isolation. *Maximum values.*

Level	Relative displacement , [cm]	Total acceleration , [m/s^2]	Seismic energy overtake
Isolator	20.0	1.2	2.0

The final conclusion is that the seismic isolation method used for NPP structures is more efficient because the requirements are easily satisfied, due to: (1) DGRS for NPP site is specific for a quick earthquake,$T_C \sim 0.4s$, which means that the building's acceleration is smaller, and (2) the structures specific to the NPP are stiffer, making that request $T_{IS} > 3T_1$ to be more easily accomplish.

3. The seismic response analysis for SSCs equipped with isolation devices at CTRF facility

It was assumed that at 100m and 108 m floor, fastening of the ColdBox (CB) and of LPCE (LP) columns was achieved using a seismic isolation system, with an eagen vibration period, $T_0 = 3s$. To compare the results it is shown the seismic response at level of relative displacement and absolute accelerations for these equipment for different types of fixing (with different types of vibration periods). For numerical calculation was used the floor accelerogram at elevation 100m and 108 m for the fixing points of these floors, as it is shown in the seismic analysis of CTRF, [10]. In Figure 5 it is shown the seismic response for ColdBox fixing points at elevation 100m, and in Figure 6 it is shown the seismic response obtained for LP fixing at elevation 108m.

ColdBox fixing: Elevation 100m. X direction. Damping = 5%

In the table below it is presented the floor accelerogram and the comparison of maximum floor accelerations in various types of fixing (T_0 = 0.2s, 0.5s, 1s - thin line - and with ID cu T_0 = 3s – thick line) and viscous damping ratio $\beta = 5\%$.

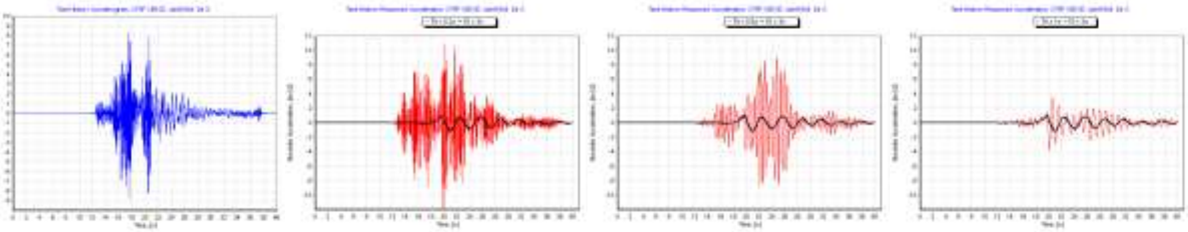


Fig. 5. *Floor accelerogram at elevation 100m for the ColdBox fixing points. Comparison between the seismic responses as absolute acceleration of equipment with different vibration period.*

LP fixing: Elevation 108m. X direction. Damping = 5%

It is presented the floor accelerogram and the comparison between various maximum acceleration values in various fixing modes (T_0 = 0.2s, 0.5s, 1s and with ID with T_0 = 3s) and viscous damping ratio $\beta = 5\%$.

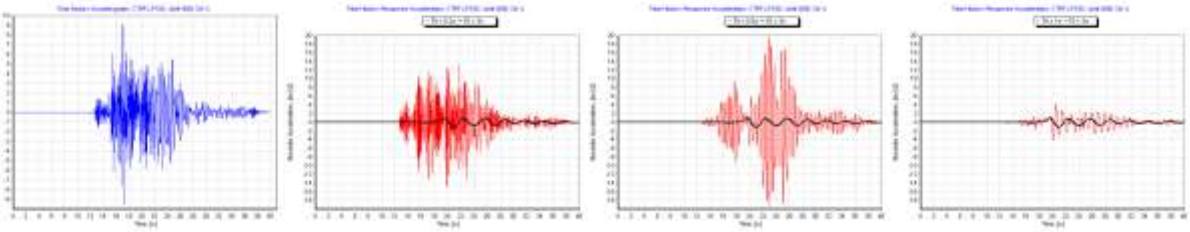


Fig. 6. *Floor accelerogram at elevation 108m for the LP fixing points. Comparison between the seismic responses as absolute acceleration of equipment of which fixing system has its own vibration period.*

It is determined that the seismic response of the equipment provided with ID it is limited to a value approximately equal to A = 1.2m/s^2 for acceleration, which means an attenuation of 7.5 times for CB (elevation 100m), respectively 8.4 times for LP (elevation 108m) towards floor maximum values. In proportion to equipment response, for 5% viscous damping ratio and for different vibration periods of the fastening system, the reduction is about 9 to 12 times (for T_0 = 0.03s/F_0 = 33Hz), 16 to 18 times (for T_0 = 0.1s/F_0 = 10Hz), 9 to 12 times (for T_0 = 0.2s/F_0 = 5Hz), 10 to 15 times (for T_0 = 0.5s/F_0 = 5Hz), respectively 3 to 4 times (for T_0 = 1s/F_0 = 1Hz function of the elevation on which they are placed. Using a maximum viscous damping ratio allowed by the methodology, $\beta = 30\%$ leads to an acceleration seismic response reduction, and mostly relative displacements, which is particularly important for the stability of the isolation system. In case of seismic isolation, $T_0 = 3s$ an increase of damping leads to a decrease of relative displacement for the duration of the earthquake, the peak value decreases with 30-35%. For total acceleration, for seismic isolation, the increase of damping leads to a decrease of acceleration for the duration of the earthquake, the peak value lowering with only 10%. A good seismic isolation involves a large ID's isolation period, and to limit de displacements in ID it is necessary also a sufficiently large damping.

Conclusions

This paper was based on the study of seismic isolation analysis methodology, the seismic action characteristics analysis and the seismic isolation devices characteristics. We wanted to acquire, improve and conceive effective mathematical methods to describe the seismic response in order to avoid the serious consequences caused by an earthquake of great magnitude and demonstrate the applicability of the isolation solution a non-nuclear and nuclear building on the Cernavoda site (city and NPP) and the SSC seismic isolation solution on a floor of the CTRF building.

The results obtained lead to the following conclusions: isolation devices must show ability to: (1) *reduction of the seismic accelerations* of the seismic isolated building to values not dangerous for people, environment and national heritage; (2) *elimination* therefore of *classical seismic qualification*, which is technically and economically expensive; (3) *limiting the strains* in the devices to safety values to ensure structural integrity and stability of the entire system; (4) *effective and without side effects dissipation of seismic energy*, aspects that provide (1) and (3) both for seismic isolated building and devices, and (5) *return to the initial position*, pre-earthquake, with acceptable remanent displacements. In this case, the structure remains displaced about 6 cm from original position because of the friction. Reduction of this remaining displacement will be done by the reduction of the friction coefficient to a minimum value (for example by lubricating the surfaces in contact during earthquake), in which case a new analysis using other parameters shall be carried out to meet (1) – (3).

The final conclusion of the study is that the seismic isolation solution must take into consideration the on site specificity of earthquakes. Vrancea is a particularly critical site for Romania because Vrancea's earthquakes are slow earthquakes, with corner periods T_C, moved toward higher values. For this reason, the seismic isolation solution must use seismic isolation systems which are calibrated for the site and objective type, which must be capable to overtake large displacements induced by the seismic response without any risks.

The methodologies, methods and procedures designed in CITON to improve the seismic qualification of SSC's can be applied to the objectives of great importance, both nuclear and non-nuclear.

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