A new approach in seismic base isolation and dynamic control of structures

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2017 NZSEE Conference

ABSTRACT: A newly developed Seismic Isolation System (SIS) approach suggests the initial definition of the Demand requirement in a form of SIS Performance Target Criteria (PTC) by using the Goal Function in the optimization process in order to get the optimal SIS Capacity. The target is to obtain the optimal 3D SIS in terms of sufficient 3D acceleration isolation and appropriate 3D relative displacements of super and substructures for a specific seismic input and the current structure having separately defined optimal elastic (natural frequencies) and damping SIS parameters.

The paper provides a general approach in 3D SIS optimization, results of analysis based on real characteristics of isolators and viscodampers and ways for practical application of the proposal for structures and buildings with a perfect 3D isolation capacity and limited relative displacements, which makes it unnecessary to arrange any special compensation actions for distribution systems.

The results of 3D SIS optimization are demonstrated by example of SIS design for a heavy and high Nuclear Power Plant (NPP) Reactor Building (RB).

1 INTRODUCTION

In general, the SIS efficiency depends on the combination of elastic properties of isolators and system damping. The tests of the 3D Floor Seismic Isolation System performed in Japan at the IHI 35-ton shaking table have confirmed an evident but unexpectedly positive influence of system damping (Ochi 1990). Upgrading the Floor Isolation System damping from 3% to 14% by changing the features of 3D viscoelastic variable dampers had a double effect in 16% increase of the efficiency of SIS acceleration isolation and at the same time in decrease by 1.5 times of relative super and substructures displacements. This brought to an idea of developing a 3D SIS with capacities that would satisfy rather controversial demands for good isolation ability and limited umbilical displacements using the optimization procedure (Vasilyev 2013).

A conventional SIS design involves the use of existing or permanently appeared new isolation devices, which have fixed stiffness and damping parameters. Subsequent seismic analysis shows clearly defined positive and negative features of the SIS devices implemented. The vertical seismic excitation and other possible dynamic impacts on the structure are usually excluded from consideration and the SIS efficiency is shown in the horizontal direction only. One more concern in using the conventional SIS practice for 3D isolation appeared after relevant experiments have been carried out at the shaking table in Japan where a full-scale building was equipped with LRB and FPB bearings and subjected to 3D seismic excitation. While in cases of 1D and 2D horizontal excitations both SI systems demonstrated good isolation parameters, the addition of vertical seismic impact has brought the building structure to a non-isolated state (Furukawa 2012).

A newly developed SIS approach suggests the initial definition of the Demand in a form of SIS Performance Target Criteria (PTC) by using the Goal Function (GF) and an optimization process. The target is to obtain the optimal 3D SIS in terms of sufficient 3D acceleration isolation including efficient vertical seismic isolation and appropriate 3D displacements for a specific seismic input and the current structure, which has separately defined the optimal elastic (natural frequencies) and damping SIS parameters. The limitation of relative displacements of the SIS super and substructures is a very important goal, which enables to simplify the SIS design and avoid making special

compensations for connecting the distribution systems of an isolated structure.

Achieving the PTC goal implies the use of an optimization process, which considers the actual characteristics of the structure and the site specific seismic spectra GMRS/UHRS as fixed input parameters. As a result of the optimization process with variable of isolator stiffness and system damping, the optimal values of SIS horizontal and vertical stiffness (basic natural frequencies of the structure) have been obtained providing the structure with necessary 3D isolation efficiency and quite limited relative displacements.

2 SIS BENEFITS AND LIMITATIONS

2.1 Type area

In nuclear power, the following benefits of SIS application (Solloguob 2017) have been determined:

- Increase in nuclear safety under seismic and other dynamic impacts.
- Essentially lower accelerations applied to structures, systems, components, equipment, distribution systems and piping.
- Decrease in weight, reinforcement and cost of structures and components.
- Possibility of using conventional or minimized seismic demand designs of structures and components.
- Possibility of aligning and maintaining the vertical position of an isolated structure and protecting it from possible soil subsidence during the whole life cycle.
- Simpler structural behavior resulting in a simpler and more defined structural analysis.
- Reduction of uncertainties in safety analysis. A structure has the only key system (SIS) responsible for seismic safety.
- Decrease in public pressure and doubts relating to seismic protection of NPP.
- Reduction of the overall cost for NPPs located in high seismic regions with the peak ground acceleration (PGA) levels over 0.3g.

At the same time the application of SIS entails some difficulties in the design and requires considering a number of new circumstances:

- More complex design and cost of slotted foundation separated on sub structure and super structure.
- Extended relative seismic displacements of internal and external structures require extra flexibility of distribution systems (umbilical problem).
- Confirmation of a specific safety margin of the SIS as the key system in seismic protection of NPP structures.

Application of the SIS in nuclear power promises great benefits in case of resolving the above problems and not only in safety issues. The average cost of a 1000 MWt NPP could be assumed as $5.0 billion in 2016 year prices and is essentially and non-linearly increases with upgrading the site seismicity PGA (Stevenson 1981, 2003). According to the evaluations the total cost of seismic engineering, the cost of seismically protected components and piping plus the construction cost for an NPP with PGA 0.4g could be considered as at least 10% of the total NPP cost. For PGA 0.6g it should be at least 20% of the overall NPP cost. In this case, the overall NPP seismic design and construction cost could be estimated approximately within the range from $500 to $750 mln. The SIS application would save at least 50% of the above sum, i.e. about $300 mln, considering some increase in the design and foundation construction costs and in the cost of SIS devices. Thus, the total cost benefit in the SIS invention could be evaluated approximately at 6% of the total cost of the NPP to be erected in high seismicity zones.

3 SEISMIC ISOLATION SYSTEM OPTIMIZATION MODEL

There are no universally optimal characteristics (elastic properties, natural frequencies, ductility and damping) for all structures, buildings and sites. These values depend to a high degree upon the following three primary parameters:

- Inertia, dynamic properties, geometry and other features of an isolated superstructure;
- Peculiarities of the seismic input. Site specific spectra, acceleration time-histories (TH), frequency content and duration;
- The goal established in achieving the isolation parameters and relative super and substructures displacements (Goal Function).

The results given below show the parameter optimization for the SIS of a PWR Reactor Building having approximately 80 meters in height and 20 meters in elevation of the Center of Gravity that corresponds to the location of the Reactor supports. Due to a large amount of calculations the optimization process required using a simplified stick RB model, which included 18 degrees of freedom (DoF) plus 3 DoF for the “seismic” mass as shown in Figure 1. Isolation Units (100 conditional devices) were modeled with linear springs and viscous elements.

Artificial time-histories correspond to the UHRS 7% damping spectra of one of NPP sites, are scaled to 0.4g in the X, Y directions and in 2/3 ratio to the Z vertical component. The comparison of the target spectrum to the artificial time-histories spectra can also be found in Figure 1.

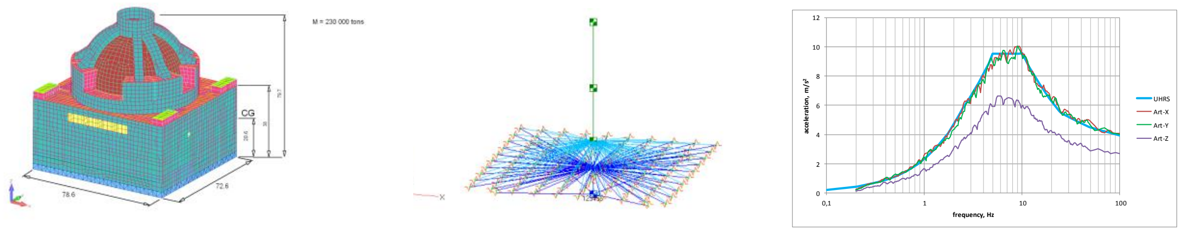

Figure 1. PWR Reactor Building, Stick Analysis Model and GRMS seismic input in the form of UHRS

A combination of the following two parameters was adopted as the Goal Function: the peak acceleration at the reactor support level (A) and maximal displacement at isolation unit (D). The goal function was written as:

$$GF = \left(\frac{A}{Aw}\right)^2 + \left(\frac{D}{Dw}\right)^2 \qquad (1)$$

Aw and Dw in formula (1) are the weight coefficients. Aw and Dw represent undesirable values of the response superstructure acceleration and its relative displacement against substructure. In this research, the following weights were adopted: Aw = 0.4g (no isolation efficiency) and Dw = 100 mm as a limit for the self-compensation ability of connecting (umbilical) distribution systems.

Nominal frequencies as well as nominal damping for horizontal and vertical directions (4 parameters altogether) are used as optimization parameters. The nominal frequency is defined by the following formula:

$$f_N = \frac{1}{2 \cdot \pi}\sqrt{\frac{C}{M}} \qquad (2)$$

The nominal damping is defined by the following formula:

$$d_N = \frac{B}{2 \cdot \sqrt{C \cdot M}} \qquad (3)$$

where:
M is the mass of the building;
C is the total stiffness of isolation units;
B is the total viscous resistance of isolation units.

It is obvious that the real frequencies and damping of the system differ from the nominal parameters indicated, so they are conditional for the purposes of analysis and simplification of the optimization process.

Preliminary calculations performed included optimization using the Hooke-Jeeves method and were carried out without any limitations set upon the parameter values. It turned out that damping growth occurred in both directions up to the critical damping value. It was subsequently decided to limit damping to 40% of the critical value in order to exclude overdamping and stiffening of the system. As a result, only two parameters remained arbitrary, i.e. the nominal frequencies in the horizontal and vertical directions. In such case, it became possible to construct the goal function surface shown in Figure 2. The nominal frequencies in the horizontal and vertical directions have the variation within the range from 0.15 Hz to 3 Hz with 0.15 Hz increments.

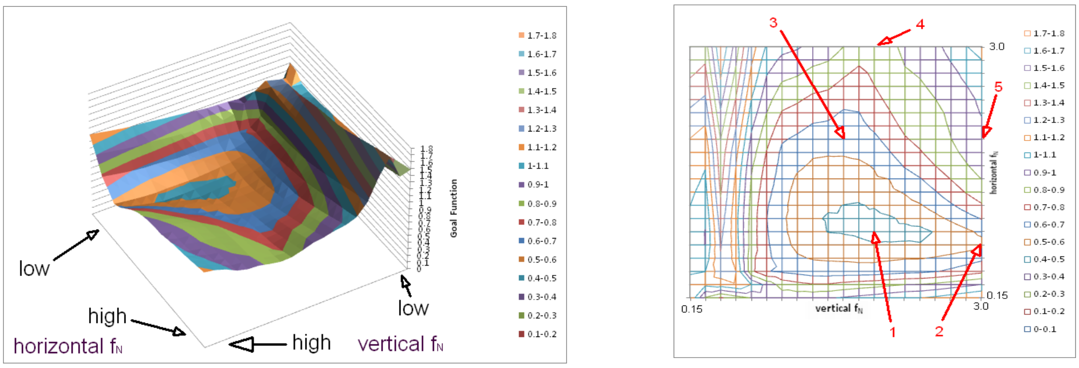

Figure 2. Goal Function Surface for 40% system damping, 3D view (left) and plane view (right)

The right picture in Figure 2 shows the goal function surface in the plane view with marked spaces and some distinguished points. In Table 1, the optimization parameters values for these points are indicated in terms of peak accelerations for the reactor supports and maximal relative displacements of the super and substructures at the corner of the SIS and the goal function.

Table 1. Nominal frequencies and response values for the principle points of the system (see Figure 2). The damping value is 40%.

Point #	Nominal frequency, Hz		Max. displacement, mm			Acceleration, g			Goal function
	horizontal	vertical	X	Y	Z	X	Y	Z	
1	0.90	1.95	24	22	23	0.13	0.12	0.15	0.49
2	0.75	3.00	28	27	10	0.11	0.10	0.21	0.59
3	1.95	1.65	8	7	36	0.19	0.17	0.13	0.65
4	3.00	1.95	5	4	32	0.23	0.22	0.15	0.88
5	1.95	3.00	12	12	20	0.22	0.23	0.21	0.98

The values of relative displacements and response accelerations given in Table 1 are incredibly low and, consequently, the analysis was performed for a more feasible damping equal to 20% of the critical damping of the system. The results for 20% damping are shown in Table 2.

Table 2. Nominal frequencies and response values for principle points of the system.
The damping value is 20%.

Point #	Nominal frequency, Hz		Displacement, mm			Acceleration, g			Goal function
	horizontal	vertical	X	Y	Z	X	Y	Z	
1	1.05	1.65	30	25	47	0.16	0.14	0.14	0.80
2	0.90	3.00	39	39	15	0.15	0.14	0.26	1.00
3	2.25	1.50	8	8	55	0.20	0.21	0.14	0.97
4	3.00	2.10	6	5	41	0.28	0.25	0.20	1.31
5	1.95	3.00	16	14	28	0.26	0.24	0.26	1.31

Looking at the results of the more realistic 20% damping picture, it could be concluded that Point 2 in Table 2 looks like the best one having low vertical displacements due to the rocking mode of the structure.

Figure 3 illustrates a comparison between the response spectra at the reactor support level for some of the nominal damping values and the nominal frequencies for the SIS and for two optimization points, 1 and 5, in Tables 1 and 2. The comparison also includes a spectrum for elevation of the structure without the SIS. The 2% damping spectra are plotted for the horizontal direction (X) and vertical direction (Z) In the Y direction, the results are practically the same as in the X direction. The 2% damping has been chosen as the characteristic value for the distribution systems and components located inside the structure.

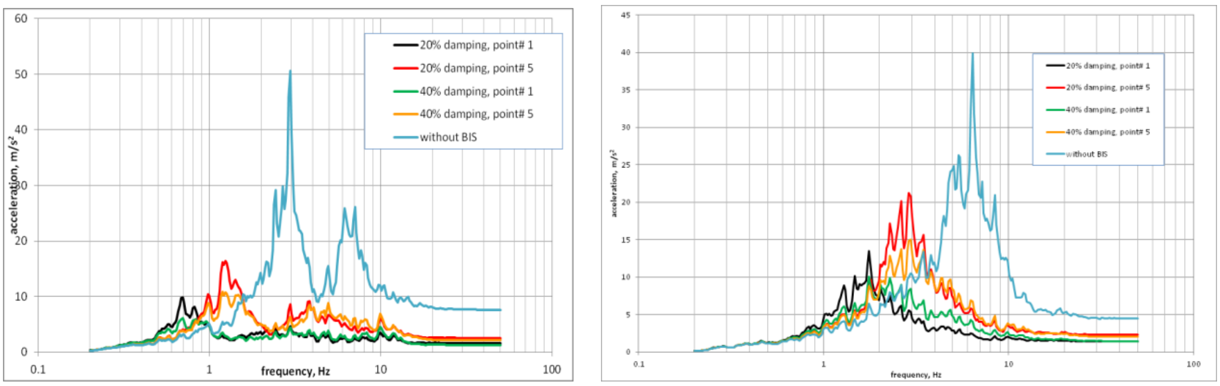

Figure 3. Comparison of the floor response spectra under seismic excitation for the structure with SIS and without SIS. X horizontal direction (left), Vertical Direction Z (right)

Unexpectedly, good results for isolation parameters were obtained not only for the horizontal direction but also for the vertical Z direction of the isolated structure as shown in Figure 3 (right).

The results of the SIS optimization analysis for non-isolated structure and isolated structure allow making some principal and important conclusions. A widespread opinion that SIS should compensate all or most of the earthquake soil motion is a delusion. To achieve good isolation parameters of the SIS it is quite enough to compensate much less than a half of anticipated soil displacements.

For the heavy and high NPP RB structure considered and the specific seismic motion defined by UHRS, the seismic input with 0.4g PGA and the specific soil conditions used, the optimal or close to optimal SIS should have:

- The first conditional natural frequency in the horizontal direction around 1.0 Hz;
- The first conditional natural frequency in the vertical direction around 2.0 Hz;
- System damping within the range from 20% to 40% of the critical value.

In this case, the SIS would have outstanding isolation parameters (up to factor 10) and quite limited

relative displacements of super and substructures (less than 60 mm) in spite of extremely high seismic excitation with PGA 0.4g. The next goal specified was to find isolation devices with needed parameters of the elastic stiffness and damping that would be able to provide the structure with such optimal values.

4. **BASIC REQUIREMENTS FOR SIS DEVICES**

In the new IAEA Report on seismic isolation (Sollogoub 2017), it has been noted that the main and very strict requirements should be applied for the base isolation devices in nuclear power applications. These requirements could be updated using some conclusions of the current study. Among them the most principal are as follows:

- The SIS should be passive with the ability to provide RB with required natural frequencies in the horizontal and vertical directions in order to achieve the target RB isolation efficiency in all DoF;
- High SIS damping ability in the horizontal and vertical directions with the range of system damping at least 20% of critical damping;
- Long-term stability in the mechanical and damping properties under all design conditions (temperature, moisture, radiation, damaging substances, fire, flood, wind, air plane crash, blast, accidental and malevolent explosions, etc.);
- Confidence on reliability of the SIS under design and beyond design basis earthquakes;
- Ability for a simple replacement of isolation and damping devices under operation conditions and to span loss of one or more devices;
- Ability to compensate short and long-term settlement (especially for structures located on soft and subsiding soils);
- Provide smooth distribution of the reaction forces and bending moments between a sub structure and a super structure;
- Availability of natural scale test results and an analytical model for SIS devices;
- The SIS must recover quickly enough to withstand large aftershocks and an inherent property that passively re-centers the system.

A search conducted on the market of existing isolation devices and dampers has shown that all the requirements stated correspond only to isolation devices represented by elastic coil spring units, provide the structure with necessary 3D elastic properties independently in the vertical and horizontal directions and 3D and, thus, the optimal natural frequencies of the system and viscoelastic dampers provide the system with necessary damping at least at 20% of critical damping and in all directions. All other known devices (according to the authors’ knowledge) are unable to provide the optimal isolation parameters of the system established by analysis.

Figure 5 shows the typical views of high capacity spring units and viscodampers and their test characteristics, which could be used in designing the optimal SIS for the NPP RB.

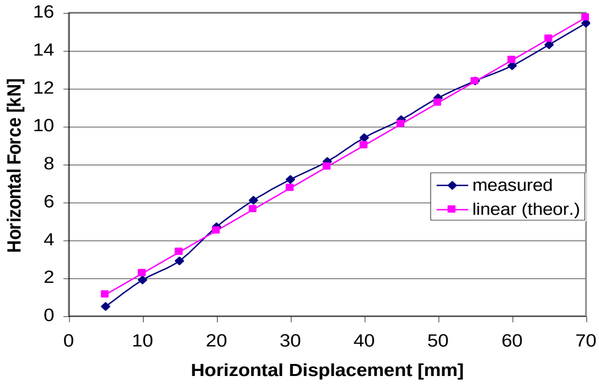

Figure 5. General view of the high capacity BCS spring unit (left) and its elastic linear characteristics.

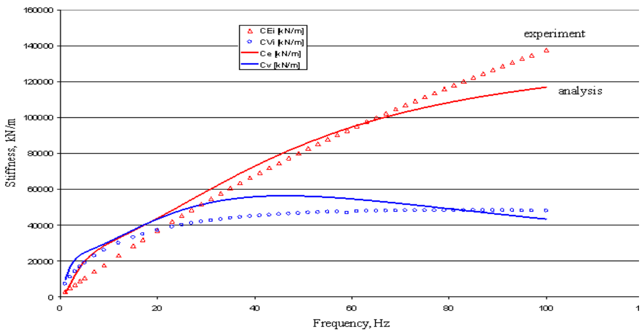

Figure 6. General view of the BCS 3D viscodamper (left) and its frequency dependent damping properties.

The SIS equipped with elastic spring units and separately installed viscodampers has the name of Base Control System (BCS) and over the course of decades has been used for vibration control and damping of operational vibration of powerful turbine decks. The new field of BCS application for base isolation of big structures has many advantages separately providing the structure with necessary natural frequencies and damping, thus tuning the system to the optimal parameters defined by analysis.

The feasibility and efficiency of the BCS was confirmed by its behavior under real earthquake with PGA 0.12g when two similar buildings in Mendoza University, Argentina, one with BCS and the other without BCS (rigid based), were subjected to the seismic motion (Stuardi 2008). The views of the buildings tested by earthquake and the location of spring units and VD dampers are shown in Figure 7.

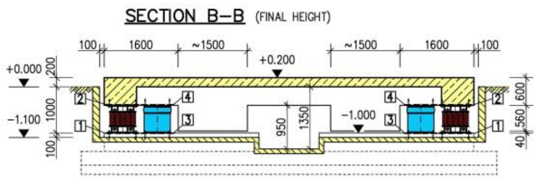

Figure 7. Isolated by BCS and non-isolated rigid based buildings (left) and location of spring units and viscodampers in the space between sub structure and super structure of the BCS isolated building (right).

The buildings were equiped with acceleration sensors and gauges to perform strain and stress comparative measurements in the structures. Figure 8 shows the time histories of accelerations at the top of these two buildings subjected to the earthquake 5.7 magnitude.

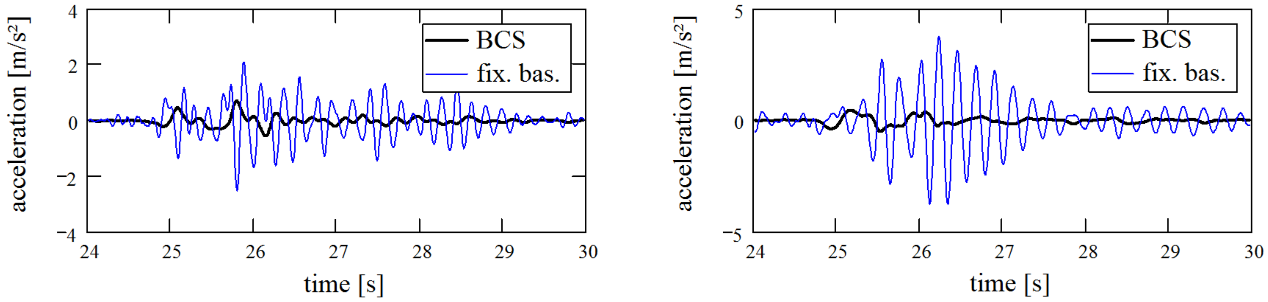

Figure 8. Accelerations at the top of two buildings, BCS isolated and non-isolated, subjected to the earthquake in the X (left) and Y (right) directions

The measurement performed for the isolated (I) and non-isolated (NI) buildings have shown that the distortion in spring elements and viscodampers are very small (around 3.0 mm). At the same time it was observed that there is a constant acceleration distribution along the isolated building height. Comparative acceleration measurements at the roofs of "NI" and "I" buildings and observation of the buildings state after earthquake have shown the following relative parameters:

- Acceleration along X, Y and Z axes: Xni/i = 0.25/0.05g Yni/i = 0.4/0.06g Zni/i = 0.06/0.07g. Roof 3D acceleration reduction achieved is more than 75%. In the vertical direction an essential amplification of accelerations was not observed in spite of non-optimal parameters of the elastic spring units in vertical direction.
- No structural damage was observed in both buildings.
- Comparative behavior of the structures: Axial forces reduction: > 60%. Shear force reduction: > 75%. Bend Moment reduction: > 90%. Story Drift reduction: > 80%

Thus, the BCS has demonstrated its outstanding isolation capability with very limited relative displacements of super and substructures under real earthquake conditions.

5 CONCLUSIONS

1. The optimization approach, proposed and developed, in defining the basic characteristics of Seismic Isolation Systems has shown new possibilities for an essential increase of the base isolation efficiency and dramatic dropping of relative displacements of the sub- and super-structures of the isolated building.
2. The developing and implementation of SIS in the BCS approach for RB and NPP structures based on coil spring supports and 3D viscodampers are feasible and could be carried out in designing NPPs located in high seismic zones with PGA levels over 0.3g.

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