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3D BASE CONTROL SEISMIC ISOLATION SYSTEM (BCS) FOR SAFETY RELATED NPPs' SSC

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INTRODUCTION

The February 6, 2023 Magnitude 7.8-7.5 earthquake in Turkey with the peak ground acceleration (PGA) close to 1.0g has shown and confirm a general efficiency of base seismic isolation (BI) for protection of buildings and structures against seismic motion. However, the information regarding behaviour of the seismic isolated structures subjected to PGA over 0.5 g is quite limited. The Akkuyu NPP, which is in the final construction phase and is located not so far from the epicentre, was also shaken by this earthquake, but without consequences due to PGA lower 0.05g.

At the same time recent investigations during Tohoku Earthquake 2011 and at the world's biggest E-Defence 1500 tons shaking table in Japan have demonstrated inconsistent results for conventional isolation systems with an essential seismic amplification in the vertical direction and limited overall efficiency.

This contribution presents results of analysis, natural scale testing and application of the first of such a kind passive Base Control System (BCS) consists of the spatial (3D) coil spring isolators and separately located 3D viscodampers. The efficiency of the BCS system were confirmed by a comparative analytical study, natural scale testing and behaviour under real earthquake.

ANALYSIS OF THE EXPERIMENTAL DATA ON BI BEHAVIOUR UNDER SEVERE TOHOKU 2011 EARTHQUAKE AND E-DEFENCE SHAKING TABLE TESTS

Recent experimental studies on the behaviour of the most widely used BI systems, such as Lead Rubber Bearing (LRB) and Triple Pendulum Bearings (TPB), during the Tohoku 2011 Great East Japan Earthquake and full-scale tests on the world's largest earthquake shaking table E-Defence in Japan, have dramatically changed the general understanding of the actual effectiveness of these types of seismic isolation.

As an example, in Table 1, developed by Iiba M. and Saito T. (2013, 2015), are presented data on the three-component motion recorded in eight buildings with seismic isolation systems of different types during the Tohoku 2011 earthquake.

Table 1: Behavior of the BI buildings under Tohoku 2011 Great East Japan Earthquake.	Site	Usage	Structure Type	Floor	Δ (km)	Main isolator and damper	Location of Sensors	ACC. (cm/s²)			Disp. of SI (cm)
								X	Y	Z	
KA	Sendai	Office	SRC	B2F 9F	172	HRB	under SI above SI top floor	289 121 142	251 144 170	235 374 524	15.7
KB	Fukushima	Office	RC	2F	178	NRB, LRB, OD	under SI above SI top floor	582 176 155	758 213 185	446 516 621	24.6
KC	Fukushima	Office	RC	3F	184	Unknown	under SI above SI top floor	411 184 154	334 226 157	324 463 581	5.8
KD	Tsukuba	Office	PcaPc	7F	334	NRB, LRB, SD	under SI above SI top floor	327 92 126	233 76 91	122 198 243	6.8
KE	Tokyo	Museum	RC	B1F 3F	382	HRB	under SI above SI top floor	100 76 100	79 89 77	84 87 90	4.2
KF	Tokyo	Office	RC	B2F 12F	386	NRB, LRB	under SI above SI top floor	104 55 94	91 41 82	58 62 104	5.1
KG	Kawasaki	Residence	PcaPc	6F	401	NRB, LRB	under SI above SI top floor	86 58 63	104 65 68	34 49 55	5.22
KH	Odawara	Office	RC	6F	457	NRB, LRB	under SI above SI top floor	136 58 63	120 134 67	47 47 48	25.2

The overall conclusion based on building inspections with seismic isolation systems after primary ground motion shocks and aftershocks confirms a sufficient effectiveness in reducing horizontal seismic loads on the structural components, as their integrity was preserved in all cases. However, the vertical component of the seismic ground motion consistently increased by 2-2.5 factor on the upper isolated elevations of the buildings, thus the combined action of weakened horizontal and amplified vertical structures' seismic response compromises an overall effectiveness of the observed seismic isolation systems.

Significant complements to the aforementioned field data from the Tohoku 2011 earthquake are the results of shaking table tests on full-scale multi store buildings with different seismic isolation systems conducted at the E-Defense test facility in Japan in the frame of USA and Japan 2010-2017 collaborative test program, Ryan K.L., et al. (2012), Furukawa S., et al. (2012), Sasaki T., et al (2012). This 3D shaking table with the 1 500 tons capacity allows an actual testing of large-scale structures and components under high-intensity multi-component seismic loads. Various types of typical 4-, 5-, and 10-story buildings with different types of seismic isolation systems were tested on the E-Defense shaking table. The tests also included the simulation of idealized one or two-component seismic horizontal loading before final test with the 3D seismic motion, Figure 1.

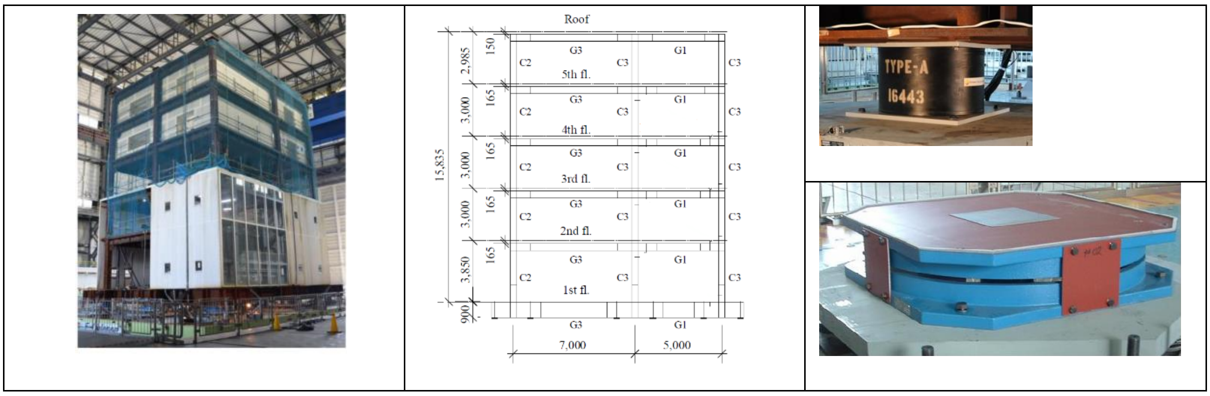

Figure 1. 5th floors test building at the E-Defense shaking table with its dimensions and TPB and LRB isolators subjected to testing. Ryan K.L., et al. (2012),

These unique comparative experiments of the seismic response of each building mode with and without a seismic isolation system (Rigid mode), revealed several significant deviations towards a substantial deterioration in the performance of all horizontal isolation systems (TPB and modified LRB/CLB) compared to the design specifications when subjected to strong or even moderate vertical seismic components in the shaking table input. The isolation effect under 3D excitation was dramatically reduced even in horizontal plane, while the vertical response of the structure increased significantly, see Figure 2.

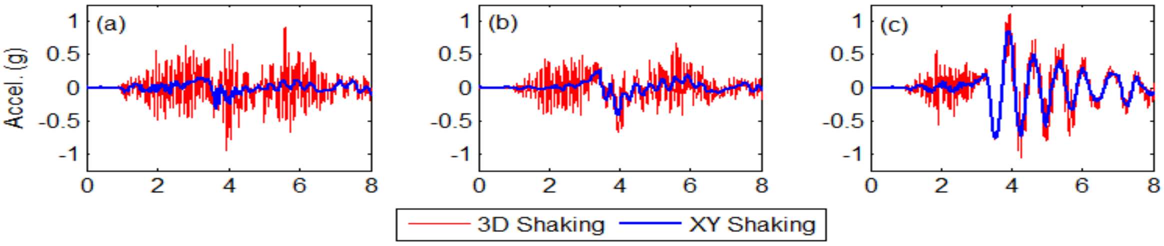

Figure 2. Horizontal seismic response (Y) of the 5th floor of the structure under horizontal X.Y (2D) excitation (blue lines) and X, Y, Z (3D) excitation (red lines). a) TPB; b) LRB/CLB; c) Fixed (Rigid) base configurations (Ryan K.L., Furukawa S., Sasaki T., 2012).

Overall, the materials of surveys and analysis of seismic resistance of buildings and structures with BI subjected to real earthquakes, as well as the data from full-scale testing of buildings with BI on the E-Defense seismic platform indicate objectively existing limitations on the effectiveness of "horizontal" types BI subjected to real three-component earthquake excitation. These limitations and peculiarities of behaviour of horizontal BI were neglected for years before and even now and should be definitely considered in BI designs.

The question arises: what causes such a significant discrepancy between analytical and experimental results in evaluating the BI effectiveness? The answer lies in the widespread use of simplified approaches for seismic analysis of BI, even at the level of construction standards, codes and recommendations, including national and international practice. The routine BI approach typically involves:

- considering only one horizontal or, at most, two horizontal components of an earthquake excitation;
- ignoring the vertical component of seismic excitation;
- neglecting the real vertical structural stiffness of the seismic isolation elements;
- simplified linearization;
- neglecting the coupling between vertical and horizontal behaviour;
- simplified assessment or ignoring of soil conditions and soil structure interaction (SSI).

As a result, the essential effects that tune the isolated structure to the dominant vertical frequencies of seismic ground motion and thus reduce the actual effectiveness of the BI are not considered in conventional analyses provide idealized positively oriented and sometime wrong picture of horizontal BI systems efficiency.

A resolution of this negative situation could be development of a multi-component passive 3D BI without increasing of the vertical response of structures and thereby restoring confidence in the application of seismic isolation systems, which has been compromised by the above-mentioned experience of past earthquakes and the results of full-scale shaking table testing of horizontal types of seismic isolation.

THE KEY IHI SHAKING TABLE TESTS OF DAMPING INFLUENCE ON 3D BI

To examine the influence of BI system's damping on isolation efficiency of the 3D isolation floor system, special shaking tests were conducted using two 3D high viscous dampers with variable damping ability developed in CKTI Lab in late 80's, Ochi Y., et. al, (1990). Having constant dimensions of damper housing and piston and constant viscosity of medium in the VD it is possible due to the design peculiarities to change dynamic stiffness and damping in device within a wide range up to two orders. It is done in order to achieve optimum damping in certain dynamic system and found its application in BI optimization.

The floor model used in the test is shown in Fig 3. The floor structure of 20 tons weight was supported by four 3D rubber air isolators. Each one of high viscous damper was installed at the middle point of each of the long two sides. The floor system was excited first by sinusoidal sweep frequency wave and then by El Centro-NS earthquake structural seismic response wave at the 5th store of the building having 2.7 Hz natural frequency in horizontal direction.

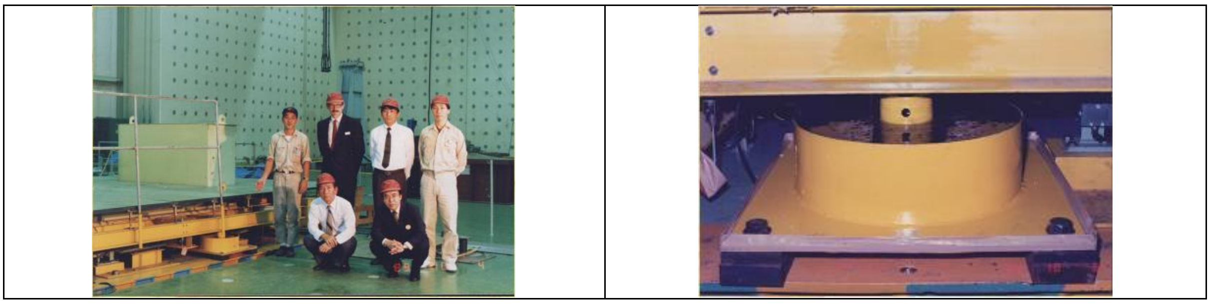

Figure 3. IHI 35 tons shaking table with isolation floor system (left) and 3D VD damper with variable damping (right), Ochi Y., et. al (1990).

The transfer function of response acceleration to input one obtained from sinusoidal sweep excitation tests are shown in Figure 4 (left). While BI damping is increased, the magnification factor is essentially decreased, but the resonant frequency does not change so much. So, high viscous damper can implement high damping force to the system with slight increase of system's stiffness.

The test results for EL Centro-NS floor response wave excitation with the highest damping ratio is indicated in Figure 4 (right).

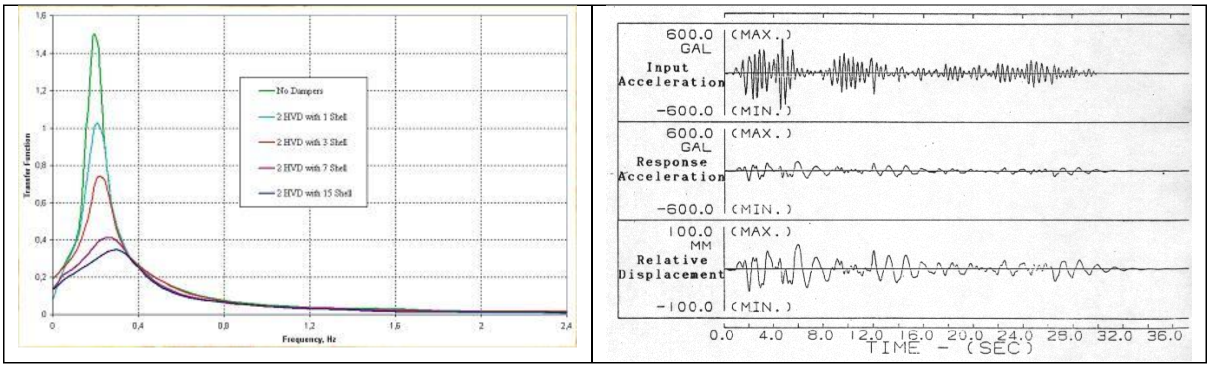

Figure 4. Results of sinusoidal sweep tests of BI with different damping (left) and tests with El Centro-NS Floor Response Wave, configuration VD 15 s (right).

In Table 2 the results of BI efficiency are explained in terms of critical damping ratio and relative BI umbilical displacements.

Table 2: BI Test Results Excited by the El Centro-NS Floor Response Wave

VD modification	Max. Input Acc. gal	Max. Response Acc., gal	Max. Relative Disp., mm	Crit. Damping Ratio, %	BI Factor
Without VD	499	161	83	3	**3.1**
VD 3 S	5 1 5	1 3 9	69	5	**3.7**
VD 7 S	5 1 5	134	61	11	**3.84**
VD 15 S	5 1 9	1 4 3	59	14	**3.63**

It could be concluded that the BI system has its optimum regarding isolation efficiency and umbilical displacements. This very important result dispels the established illusion that BI needs to compensate all earthquake ground motion as much as possible while the highest isolation efficiency could be achieved with a relatively low value of umbilical displacements by damping optimization. It opens the door for developing of highly efficient 3D BI with optimum stiffness values separately in horizontal and vertical directions and optimized 3D damping with limited umbilical displacements and no necessity in using special compensation measures (joints) for distribution systems connected building’s sub and superstructure.

BCS SEISMIC BASE ISOLATION SYSTEM

According to our knowledge the most effective and reliable passive 3D BI system is the Base Control System (BCS), Stuardi J. (2008), Sollogoub P. (2020), Nawrotzki P., (2022), Belyaev V. (2023).
The BCS consists from separately installed 3D helical spring units and 3D viscous dampers provides to the isolated structure necessary BI flexibility in horizontal directions and amortization in the vertical direction with a close to the optimal BI damping reduces umbilical effects to an appropriate relatively small range, Figure 5.

Figure 5**.** BCS high capacities 3D spring unit and 3D damper installed between sub and superstructure (left, right). Installation of the BCS for the multistore structure (middle), P. Nawrotzki, et. al, (2022).

In Table 3 are shown typical range of properties of the BCS isolation system provide the most efficient seismic isolation for structures in all spatial directions. Specific parameters of the BCS should be chosen by optimization procedure considering peculiarities of input seismic motion, soil conditions, SSI effects and dynamic properties of the structure.

Table 3: Typical range of the BCS properties

Typical BCS Characteristics	**Parameter**	**Comment**
Conditional BCS Structure's Vertical Frequency [Hz]	1.5 – 3.0	Provides mitigation of structures' seismic response in vertical direction
Conditional BCS Structure's Horizontal Frequency [Hz]	0.5 – 2.0	Very efficient reduction of seismic demands in horizontal direction
Damping Ratio [%]	10-25	Upgrading of isolation and dramatic mitigation of umbilical displacements

Comprehensive full-scale experimental studies of the 3D spring supports and 3D dampers have allowed for the development of refined non-linear analytical models of the BCS system, as well as linearized models which have been used for analysis of many structures, Figure 6.

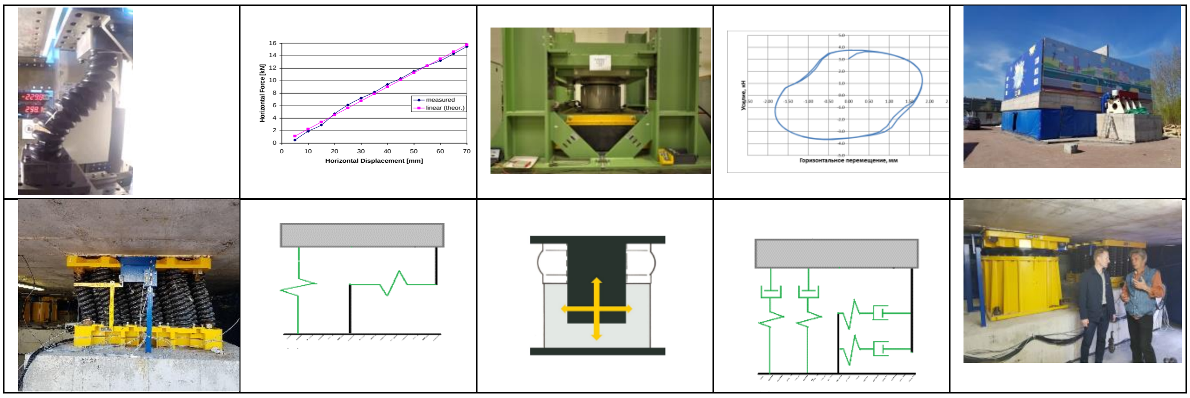

Figure 6. BCS natural scale testing and analytical models of the spring, spring unit and 3D damper. Testing at SIST Inverse shaking table with variable mass of structure (400-3000 tons) and pushing force 1050 tons (right). Nawrotzki P., et. al, (2015, 2019, 2022).

BI SYSTEMS COMPARATIVE STUDY

Analytical studies have been conducted on the behaviour of typical nuclear power plant reactor buildings with various types of seismic isolation devices under intense seismic excitation, Fig. 7.

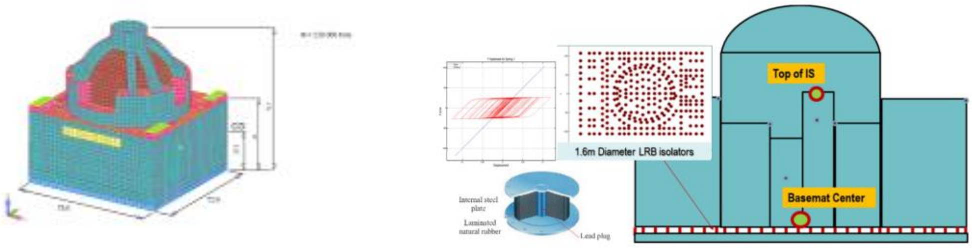

Figure 7. NPPs' reactor buildings subjected to comparative BI study by Vasilyev P. (2013), left and Chiosel D. (2019), right.

The figure 8 shows the analysis results of the very massive NPP VVER-1200 Reactor Building with a height over 60 meters, installed on the BCS system, for a seismic ground motion with PGA 0.4g, Vasilyev P. (2013). The spectra of the seismic response of the structure for the horizontal and vertical directions (Y, Z) are given for an elevation of reactor's supports. The upper curves refer to the variant of the rigidly supported building and all other curves to the BCS with different damping.

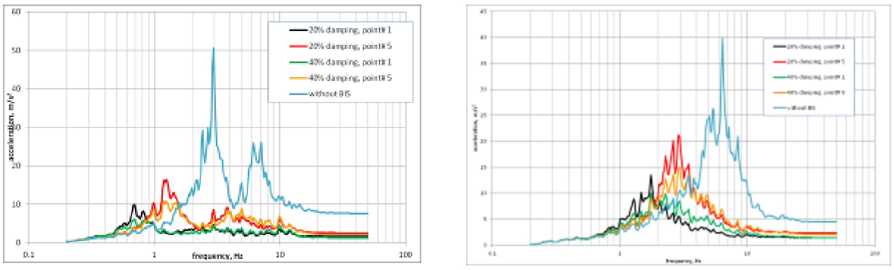

Figure 8**.** In-Structure Response Spectra for horizontal (left) and vertical (right) directions with different range of SIS system's damping (20-40%). Vasilyev P. (2013).

Obviously, the use of BCS allows not only to provide good isolation parameters in the horizontal plane, but also to reduce the amplification of the seismic response of the building in the vertical direction, which is not achievable for the most common types of seismic isolation.
This effect was also confirmed by independent researchers who conducted comparative analyses of the effectiveness of different types of seismic isolation LRB, TPB and BCS for the same type of structures and for the same seismic conditions, performed in accordance with the ASCE requirements.

As an example, Fig. 9 presents the results of a probabilistic comparative study of the LRB and BCS seismic isolation systems effectiveness, considering the coherence and incoherence of the seismic impact and the influence of soil conditions for the NPP reactor building, shown in Fig. 5 (right), Chiosel D. (2019).

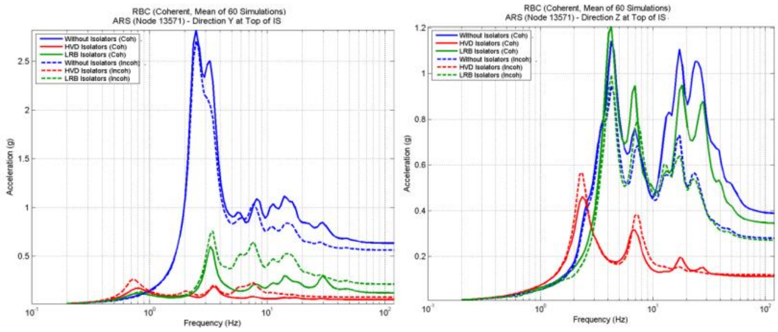

Figure 9**.** In-Structure Response Spectra (coherent) for horizontal Y direction (left) and vertical Z direction (right). Without BI (blue curves), LRB (green), BCS (red), Chiosel D. (2019).

The results presented show that the BCS system is better than LRB in terms of efficiency not only in the vertical direction, as proven by previous studies, but also in the horizontal direction, providing significantly better overall seismic isolation of the building. This positive result is achieved due to the high damping in the BCS system.

Another proof of the BCS effectiveness was performed by LRB, TPB, BCS comparative analysis of a typical NPP's fuel storage building, Figure 10. Two types of seismic analysis with PGA 0.4g of this building were performed - deterministic with a rock soil property and probabilistic, considering the medium soil conditions and the incoherence of the seismic motion.

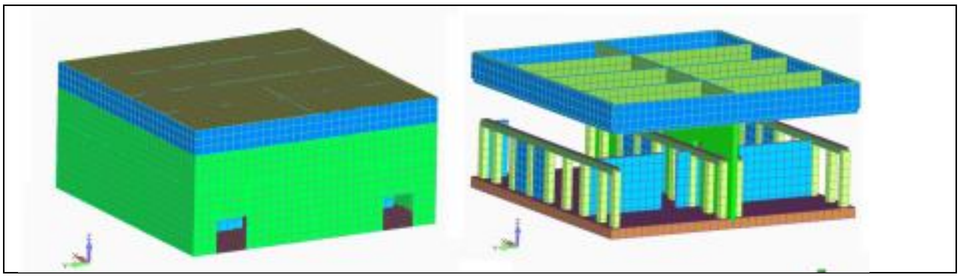

Figure 10**.** Analytical model of the fuel storage building for the comparative seismic analysis without BI (Rigid base) and with three types of BI (LRB, TPB and BCS). Kultsep A. (2022).

In the Figure 11 are shown the results of a deterministic analysis of a building located at a rock site with rigid anchoring (Rigid) without isolation and with three cases of seismic isolation systems as LRB, TPB and BCS. It should be noted that analytical models for isolators were developed on the basis of available test data of these devices. On the left are the In-Structure Response Spectra for the horizontal Y direction, and on the right for the vertical Z direction, Kultsep A. (2022).

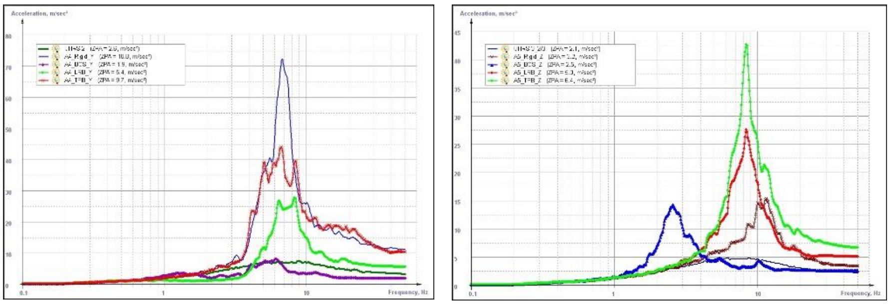

Figure 11**.** Comparison of In-Structure Response Spectra for 4 cases of structure placed at the rock site. Left picture horizontal Y direction: Blue curve without BI, Red TPB, Green LRB. Purple BCS, Dark green Uniform Hazard Response Spectrum (UHRS). Right picture vertical Z direction: Green TPB, Red LRB, Brown without BI, Blue BCS, Black UHRS, Kultsep A. (2022).

In this study, BCS demonstrated the best seismic isolation performance in both horizontal and vertical directions. Noteworthy is the large amplification of the vertical response for the LRB and TPB systems compared to the "Rigid" case. This analytical result confirms the data of field experimental studies and E-Defense shaking table discussed above.

The results of a comparative study of seismic response of the same fuel storage building shown in Figure 10, placed at the average soil conditions in deterministic and probabilistic formulations are presented in the Fig. 12, Chiosel D. (2022). Four cases of building support were under investigation: Rigid support (without BI) and BI with LRB, BCS and TPB. An improved non-linear analytical model for the LRB system was used. The Y and Z spectra in the figure 12 are built for the top elevation of the building.

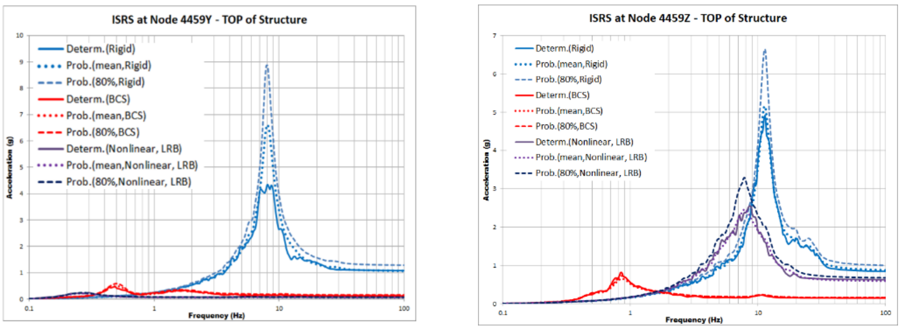

Figure 12**.** Comparison of deterministic and probabilistic In-Structure Response Spectra for rigid base structure without BI and with BI. Blue curves Rigid, Purple LRB, Red BCS, D. Chiosel (2022).

The analysis performed showed approximately the same efficiency of the LRB and BCS systems for the horizontal Y direction and higher efficiency of the BCS isolation system for the Z direction, as in all previous studies mentioned above.

BCS EFFICIENCY. CONFIRMATION UNDER REAL EARTHQUAKE

The efficiency of the BCS was confirmed by its behaviour 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, et.al, 2008). The views of the buildings tested by earthquake and the BCS efficiency are shown in Figure 13.

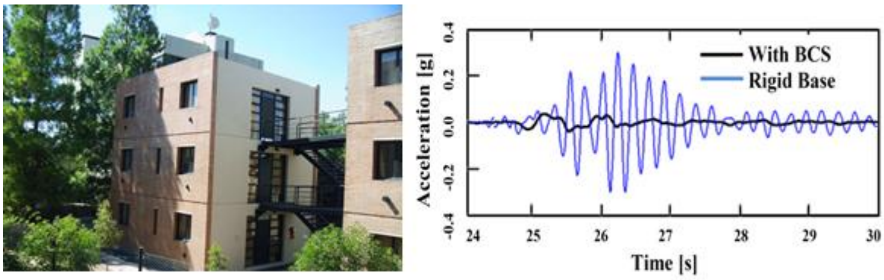

Figure. 13**.** Two similar structures: BCS isolated and rigidly supported (left). Accelerations in X horizontal direction at the top of the buildings, (right), P.Nawrotzki (2022).

Comparative measurements of non-isolated (ni) and isolated (i) buildings have shown the following relative factors:

- Maximal acceleration along X, Y and Z axes at the roof:
  Xni/i = 0.25/0.05g; Yni/i = 0.4/0.06g; Zni/i = 0.06/0.07g.
- Direct structural measurements of the (ni) and (i) in %:
  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 (umbilical) displacements of super and substructures under real earthquake conditions.

CONCLUSION

The BCS seismic isolation system provides an outstanding efficiency including building vertical response along with very limited umbilical displacements of sub and superstructure. The effectiveness of the BCS was confirmed by comprehensive natural scale tests, analysis and BCS behaviour under real earthquake.

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