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SEISMIC PROTECTION OF NPP STRUCTURES BY 3-D BASE CONTROL SYSTEMS

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ABSTRACT

Designing nuclear power plant structures requires careful consideration of all possible load cases, including seismic risk and safety. This offering illustrates seismic control strategies based on proven 3-dimensional Base Control Systems (BCS) implemented on a wide range of machinery and equipment, such as large turbine foundations, and can potentially be used for auxiliary buildings and reactor buildings. Experimental and numerical investigations as well as measurements of real structures underline the efficiency of a BCS. These systems consist of helical steel springs and viscous dampers. The vertical and horizontal flexibility of springs provide a 3-D elastic support system that allows the tuning of the rigid body modes into the low frequency range. The viscous dampers generate a high degree of structural damping in all rigid body modes, controlling amplification of loads and displacements. This mitigation strategy yields drastically reduced seismic acceleration levels, internal stresses and in-structural response spectra. For building structures, it is also recommended to have a closer look at the soil reactions due to seismic excitation. Without mitigation system high pressures develop, and in some cases, even uplift at the edges of the building can be expected. Providing horizontal flexibility alone may not be sufficient here, especially when consider strong vertical ground shaking. Thus, a 3-dimensional support strategy should be investigated. In addition to the advantages regarding seismic demands, the same support devices could be used for the vibration isolation of buildings, machinery and equipment. Additional extraordinary load cases, e.g. aircraft impact, are also covered by the elastic support system. This paper provides practical considerations for the layout and use of Base Control Systems, details of executed projects and results of numerical investigations. It documents the high efficiency of the investigated control system for the protection of structures against seismic impacts in horizontal and vertical directions.

INTRODUCTION

This contribution concentrates on the reduction of structural responses due to seismic excitations. The first section covers the fundamentals of 3-D Base Control Systems and general seismic protection strategies. In the following chapters several details of executed projects in the field of nuclear power plants are presented. Calculated and measured results are used to illustrate the general applicability of the stated control systems.

The majority of seismic protection strategies and the detailed design for many structures only treat the horizontal effects of earthquakes; respectively the horizontal isolation utilizes devices that provide low horizontal frequencies (long periods) in combination with a very high vertical stiffness. These elements (e.g. rubber bearings, lead rubber bearings, friction pendulum bearings) are well-known as Base Isolation System (BIS). Protection systems that use helical steel springs and viscous dampers achieve flexibility and damping in all three spatial directions, and are hence referred to as 3-D Base Control Systems (BCS). Key differences between the two distinct systems are presented in Table 1.

Table 1: Main characteristics of Base Isolation Systems (BIS) and Base Control Systems (BCS).

	BIS	BCS
Horizontal stiffness	Extremely low	Low
Vertical stiffness	Very high	Medium
Horizontal acceleration	Very low	Low
Stress / Strain level	Very low	Very low
Vertical efficiency	No / amplification	High
Displacement	Very large	Medium
Vertical soil reaction	Large	Medium
Higher modes	Problematic	Nearly no effect
Exchange of devices	Difficult	Easily possible
Bearing capacity	High	Medium – high
Vibration isolation / protection against structure borne noise	No	Yes (integrated)
Aging / design life	Problematic	No problem
Adjustment / leveling of structure	Difficult	Standard procedure
Control / leveling of vertical forces	No	Easily possible
Adjustment / leveling due to soil settlement	No	Easily possible

Both mitigation systems are suitable for the reduction of seismic demands, depending on the frequency content of the earthquake. In summary the BIS could be described as a very efficient horizontal seismic protection system, while the BCS yields a 3-dimensional protection effect, in combination with several noteworthy advantages.

PRINCIPLES OF 3-D BASE CONTROL SYSTEMS

The Base Control System (BCS) consists of devices with helical steel springs and viscous dampers. The spring elements are placed below the base of the structure to carry the gravity load. They are designed to provide sufficient safety margin to bear extraordinary excitation from seismic or airplane crash loads in all spatial directions. The elements possess linear load deflection curves in vertical and horizontal directions with nearly no dependency between the horizontal and vertical stiffness values. Thus, their numerical description is comparatively simple and the behavior of the spring supported structure can be easily assessed. Highly efficient 3-D viscous dampers are arranged in parallel to control resonance amplification in all spatial directions. Their properties can be described by the damping resistance values for the horizontal and vertical directions. Typical elements are shown in Figure 1.

Figure 1. Base Control System below reinforced concrete structure.
3-D Viscous damper (left), Spring element (right).

The arrangement of elastic devices leads to a change of the mode shape of the supported structure and to a reduction of the dominant frequency, or elongation of the fundamental period of the system. This frequency decrease could reduce the seismic demands by more than 60 %, depending on the details of the seismic input. As expected, considerably reducing frequencies yields higher relative displacements. In general, it is required to find an optimum between the reduction of seismic accelerations and the occurring displacements. The viscous dampers serve to limit displacements of the isolated structure by physical constraints (e.g. for beyond design cases) and by absorbing kinetic energy by providing a high degree of modal damping. An increase of structural damping from 5 % to 15 % causes a reduction of absolute accelerations, structural stresses, strain, displacements etc. in a range of about 25 % according to American Society of Civil Engineers (2017). This mitigation strategy could be combined with the frequency reduction to optimize system performance. In summary, a BCS allows the tuning of rigid body mode shapes into the low frequency range while also considerably increasing structural damping. This seismic protection strategy results in significantly reduced seismic acceleration levels and corresponding structural advantages for the supported structures, as presented also in Nawrotzki et al. (2013).

The BCS elements range in bearing capacity, horizontal and vertical stiffness properties, ratio between vertical and horizontal stiffness and in the damping resistance values in all directions. These parameters can be adjusted to accommodate project specific requirements. One of the first parameter that is investigated for each project is the stiffness ratio. Using a higher stiffness ratio (k_v/k_h) of the spring has proven advantageous for several executed projects. This value is used to control the seismic motion of the elastically supported system and could lead to a substantial reduction of acceleration amplification as shown in Basu et al. (2010). Using a low stiffness ratio could lead to a horizontal mode shape including a large rocking component. For projects, where this rocking motion is undesirable, a higher value for the vertical to horizontal stiffness ratio is preferred. Typical favorable values for this ratio are between 5 and 8. The increase of the stiffness ratio yields a mode shape with less rocking. The addition of viscous dampers leads to larger damping ratios in the dominant mode shapes. Depending on the details of the project (i.e. supported mass, dimensions, material damping, requirements, etc.) often a combination of a vertical frequency around 3 Hz and horizontal frequencies around 1 Hz, both with a corresponding damping ratio between 10 % and 30 %, presents an optimum solution. More detailed investigations of optimization criteria according to Kostarev et al. (2018) show quite similar results. As a result of the reduced frequencies and increased structural damping the seismic demands of the structure in terms of absolute accelerations, base shear etc. can be reduced drastically by using a 3-D Base Control System. These mitigation effects have been verified by theoretical and experimental research. A corresponding example is the investigation of a BCS for a massive concrete structure by Gomez et al. (2012). The prototype tests on a shaking table showed a high correlation between previously calculated results and measured results.

Especially worthy of mention is a building project in Mendoza, a high seismic zone of Argentina. In 2004 two identical apartment buildings were built. The first building consists of a conventional “fixed-base” foundation and the second adjacent building is supported by a Base Control System. Both structures contain three floors of reinforced concrete and masonry infill. The dead load of one building amounts to about 260 metric tons. The main dimensions are about 8.2 x8.7 m in plan with a height of 9 m. After commissioning, the National Technological University of Mendoza installed seismic accelerometers in both buildings. In 2005 the calculated efficiency and the predicted general feasibility of the BCS supported structure was tested against a real earthquake with a peak ground acceleration of 0.12 g. A picture of both buildings and one exemplarily comparison of measured results are shown in Figure 2.

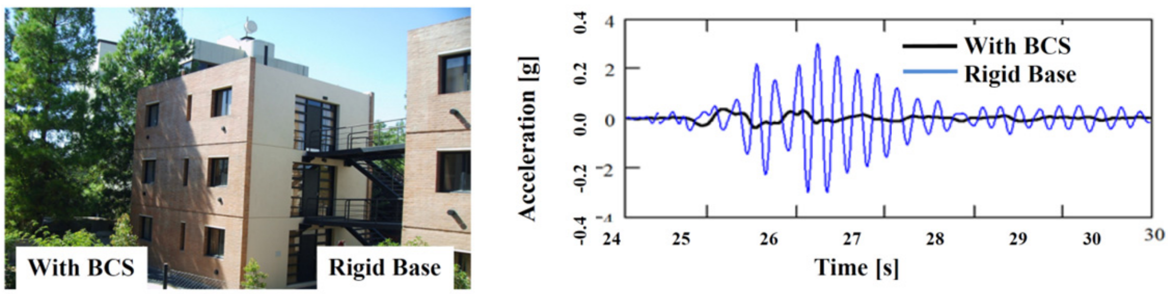

Figure 2. View of both buildings and measured seismic responses at the roof.

The acceleration values at the base controlled building are reduced by more than 70 % in comparison to the unprotected building. In this context it should be noted that these results were achieved with relatively small displacements (several millimeter only) within the BCS devices. After a minor adjustment of the characteristics of the initial analysis model due to the measured results, it was shown by Stuardi et al. (2008) that corresponding reduction factors can be found also in regard to internal stress and strain values as well as to subsoil reaction loads. Axial forces in columns were reduced by more than 60 %, shear forces by more than 75 %, and critical bending moments were decreased by about 90 %. Thus, the BCS has successfully demonstrated its outstanding seismic protection capability for a building structure under real seismic conditions.

PROTECTION OF MACHINERY

Elastic support of machinery is the state-of-the-art for efficient vibration isolation. Devices with helical steel springs are arranged below turbine generator sets, feed water pumps, fans, emergency diesel generators and other machine foundations in nuclear power plants. A typical view of vibration isolation devices below a concrete deck supporting a large turbine is shown in Figure 3.

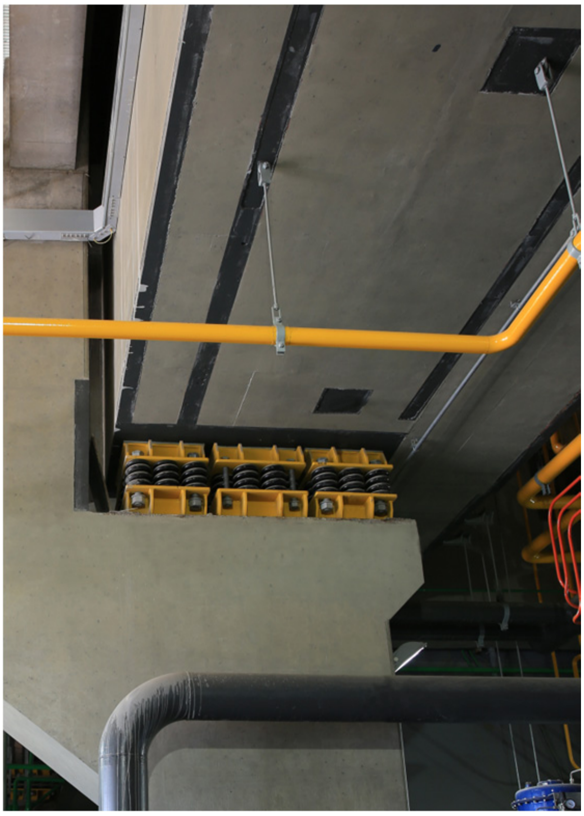

Figure 3. Elastic support below turbine deck.

The vibration isolation provided by the spring support allows for clever integration of machine and building foundations. In this case, the spring element parameters can be optimized, as explained in the previous chapter, and integrated with viscous dampers to reduce seismic demands. Figure 3 clearly shows the turbine pedestal foundation below the spring devices also supporting adjacent structure of the machine house. Furthermore, this leads to an optimized layout of the complete machine building. Its seismic behavior in terms of relative displacements between structures, induced accelerations at the shaft level of the machinery, resulting structural stresses and soil pressure is improved, as discussed in Basu et al. (2010).

There are countless examples of elastically supported diesel generator sets – not only to meet stringent vibration isolation criteria but also for seismic protection of critical [Class 1E, IEEE-308 (2013)] machinery. The efficiency of 3-D Base Control Systems has been proven by experimental and numerical evaluations, for example presented in Choun et al. (2007). After the Fukushima event in 2011 an increasing number of emergency diesel generators are being installed on BCS to ensure seismic safety. As an example, existing nuclear power plants like Goesgen NPP, in northern Switzerland, are undergoing efforts to update protection mechanism for systems in operation since 1979. They initially looked at the bunkered emergency diesel gensets, which play a fundamental role in the secured safety system. The previously installed spring and damper devices below these machine sets were replaced by new spring-damper element combinations during the first shutdown of the plant after the Fukushima event, as described by Kaulbarsch (2013). The increase of seismic input and safety margin during an earthquake was the main reason for the replacement of the devices. This highlights the need to implement a protection system that can be adjusted and/or easily replaced for changing requirements.

PROTECTION OF EQUIPMENT

In addition, there are scores of sensitive components in a nuclear power plant. A representative example of a spent fuel storage tank is presented below.

The dimensions of the pool structure are about 20 x 10 m in plan with a height of approximately 14 m. During operation the maximum total mass amounts to 6000 metric tons. This structure is located in a high seismic zone of Switzerland and is supported on a 3-D Base Control System, arranged between pool and surrounding building structure, as shown in Figure 4. The BCS was installed in 2008.

Figure 4. BCS below spent fuel storage tank.

The seismic input can be described with a zero period acceleration of nearly 0.5 g of the floor response spectrum. The arrangement of a seismic protection system for the fuel pool was required to reduce potentially high response accelerations within the structure. The waves generated on the water surface must not overflow the top of the pool walls and the stored fuel racks should not collide. The BCS consists of spring groups in housings and spring damper combinations. The devices were designed for the above-mentioned requirements to yield relatively low frequencies of the system in combination with an increase of structural damping. The devices remained in a pre-stressed stage during the construction of the pool structure. Thus, they acted as a rigid support and construction activities could proceed without special considerations. They also allow for easy adjustment of the system in case of differential settlement of the substructure or in the case that any other modifications become necessary during the lifetime of the structure. One further advantage of this kind of elastic support system is that the access to the devices is easy and ensured, thus a visual check of the elements is always possible.

In addition to the seismic excitation it was also required to consider the effects due to aircraft impact. It can also be shown that due to the low frequencies of the base controlled spent fuel storage tank the high frequency content of the impact is filtered out by effective vibration isolation. Thus, the BCS is capable of protecting structures against seismic effects as well as impact loads, such as expected from aircraft crash. In addition other equipment like switchboards, control rooms and electrical cabinets could use a similar protection strategy, as discussed in Siepe and Nawrotzki (2015).

PROTECTION OF BUILDINGS

In nuclear power plants some parts of buildings or entire buildings have to be protected against extraordinary load cases, like seismic events. Nowadays there are several hundred buildings worldwide supported on helical steel spring elements. As described in Nawrotzki (2007) in most of these cases the elastic support is required to provide vibration isolation, e.g. from traffic or train pass-by. The high frequency excitation in vertical direction, which may disturb or endanger the building structure, is filtered out by the low frequency of the support system. In seismically prone areas this support strategy is modified and optimized to consider also the corresponding effects of earthquakes. Viscous dampers are installed and the parameters of the spring devices are adjusted, as explained in a previous chapter. Thus, it should be possible to install NPP structures or even the whole nuclear island on top of a 3-D Base Control System, as shown in the sketch of Figure 5.

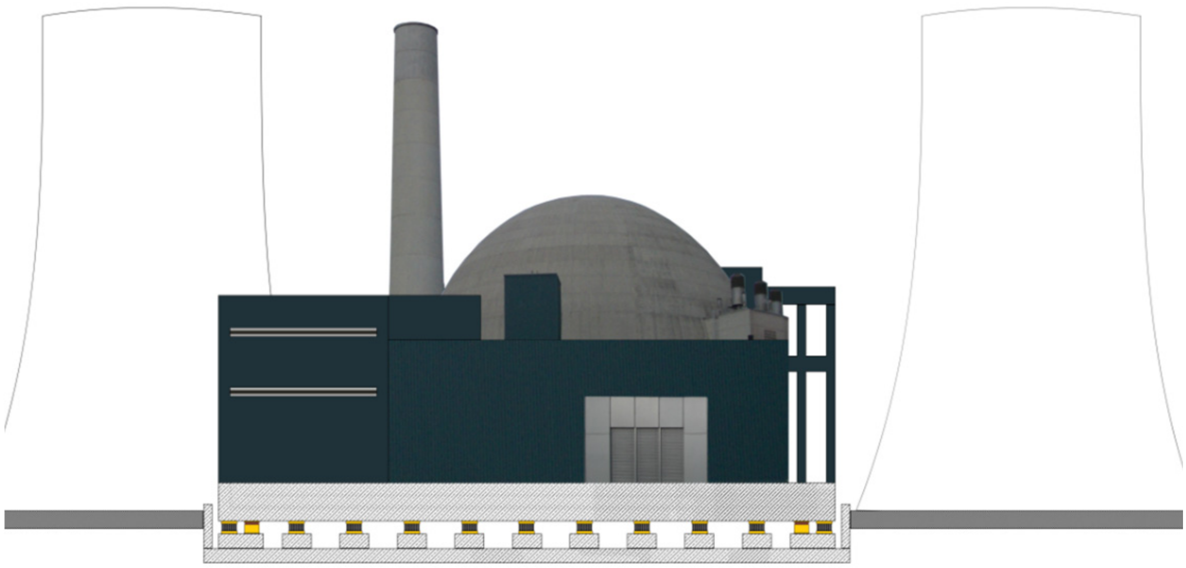

Figure 5. Principle sketch of a Base Control System below NPP structure.

Due to the arrangement of the BCS the resulting seismic accelerations and internal forces inside the building will be relatively small. Furthermore, no significant values of in-structural relative displacements are expected. In this regard the relative motion between building and vicinity are more important, as corresponding connections like steam pipe systems must be designed for such relative displacements.

Numerical investigations of a typical NPP building structure are performed to present more details of the mitigation effects of the Base Control Systems. Therefore, two mostly identical finite element models are prepared. The first model consists of fixed restraints at the base mat. The second model is supported by a BCS. Total weight of one structure is assessed with 150,000 metric tons. The longitudinal axis is the x-axis, the transversal axis is the y-axis and the z-axis represents the vertical axis. The computer model and the assumed seismic input are shown in Figure 6.

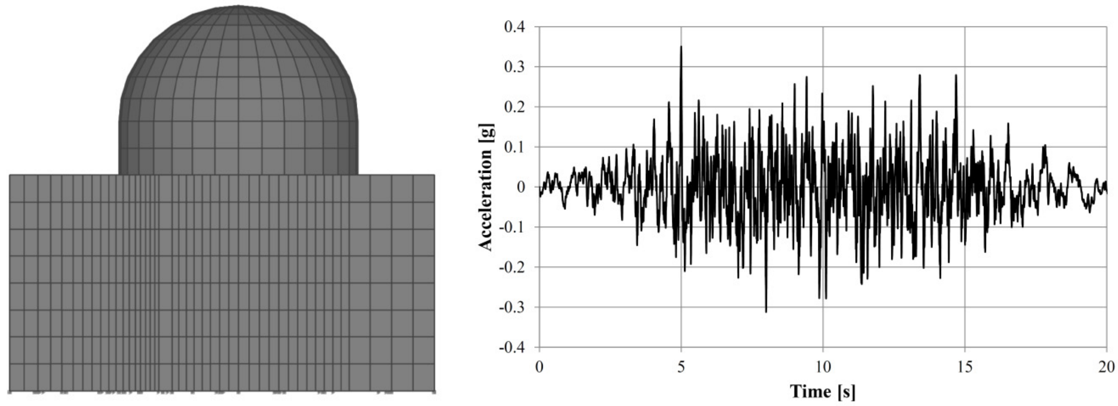

Figure 6. Finite element model and base excitation.

As a simplified assumption the above time history is used for a simultaneous excitation in all three spatial directions, neglecting the effect that the horizontal and vertical seismic input data usually differ. During a short iterative process, the parameters of the BCS are adjusted and optimized. Finally, a vertical support frequency of about 2.5 Hz and first horizontal modes with eigenfrequencies of about 1.1 Hz are chosen. The maximum seismic responses in terms of base shear and absolute accelerations at the roof of the structures are evaluated. The comparison of both models shows that the BCS yields a reduction of base shear and accelerations by more than 75 %. There is also a large reduction effect in the vertical direction. Figure 7 shows results in detail.

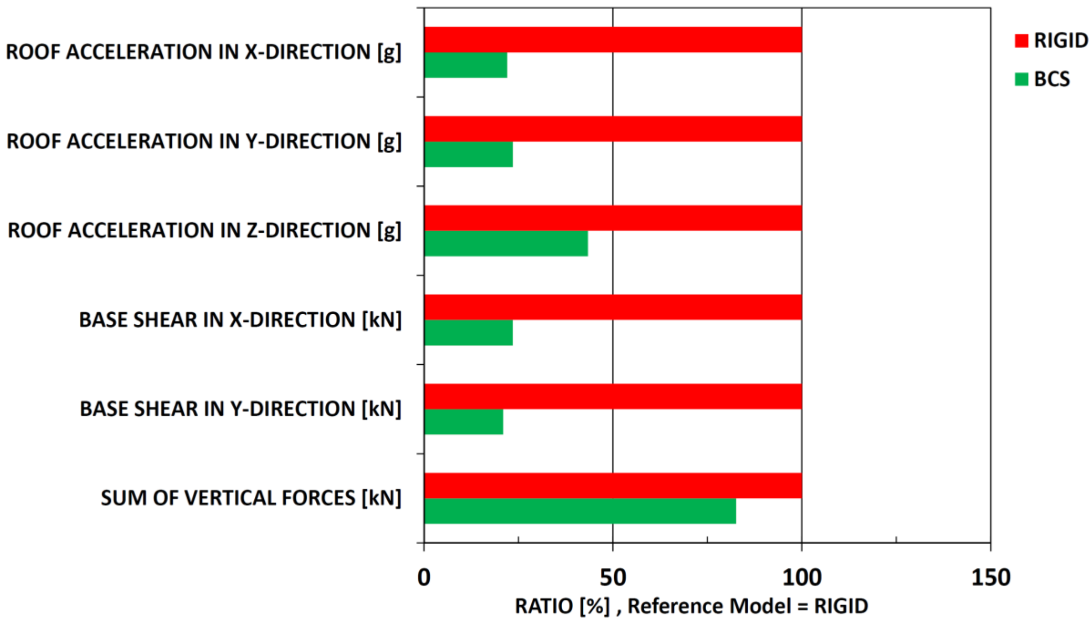

Figure 7. Efficiency of a 3-D BCS.

The first case (“RIGID”) represents the model with fixed restraints and the second option (“BCS”) indicates the model with Base Control System. Based on the previous results it can be concluded that even the internal stress and strain values will be reduced in a same order of magnitude. Furthermore, it is important to calculate the floor response spectra, typically used for the layout and design of sensitive equipment inside structures. Figure 8 shows the in-structural response spectra at a higher elevation of the building. As the results in both horizontal directions are quite similar only the x-direction results are shown.

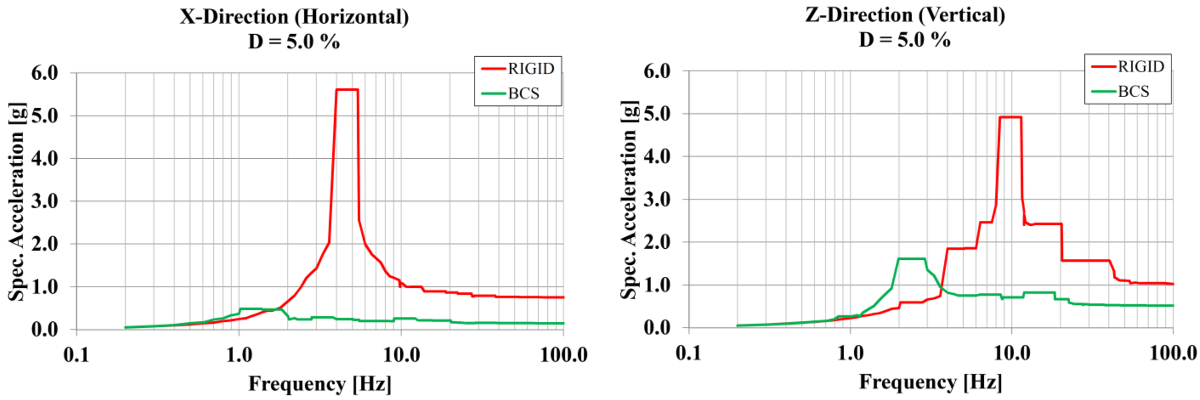

Figure 8. Comparison of floor response spectra with and without Base Control System.

The curves consider a frequency widening of ± 15 %. Due to the aforementioned main frequencies of the base controlled structure the green curves of the BCS show small narrow peaks around 1.1 Hz for the horizontal and around 2.5 Hz for the vertical direction. This result is unavoidable, but the affected frequency range does not play a major role for the equipment installed at these locations. Above these frequencies the floor response spectra of the building with BCS are considerably lower than the spectra of the unprotected structure. The corresponding efficiency provides an important advantage for the design and behavior of the equipment.

The described results can be found also for other NPP structures, using different sets of time history curves, as described in Nawrotzki and Siepe (2014). It can be summarized that the arrangement of a 3-D Base Control System yields a significant reduction of absolute accelerations, base reactions and spectral values of the floor response spectra in a wide frequency range.

CONCLUSION

Following a short brief outline of the principles of 3-D Base Control Systems and the corresponding seismic mitigation strategies several examples for the protection of structures were discussed. Calculated and measured responses show that the applied control system yields a very significant reduction of accelerations, base reactions and spectral values of floor response spectra in all spatial directions. The use of BCS should be further investigated for practical application in Nuclear Facilities.

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