# SEISMIC PROTECTION OF MACHINERY, BUILDINGS AND EQUIPMENT OF NUCLEAR POWER PLANTS BY USING 3-D BASE CONTROL SYSTEMS

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## ABSTRACT

Safety in nuclear power plants is of particular importance and the re-qualification of existing nuclear facilities and the intention to build new power plants in high seismic zones bring up the discussion about required seismic protection. Elements, consisting of helical steel springs and viscous dampers are used for the elastic support of machinery, equipment and buildings. As Base Control System (BCS) the same devices lead to one type of passive seismic protection system. Due to specifically designed stiffness and damping properties these systems not only protect against horizontal seismic forces but also prove highly efficient against horizontal and vertical excitation. Internal stresses and acceleration amplification can be decreased when these systems are applied.

Some examples of machinery and equipment are offered showing the advantages and improved seismic performance of these structures. For a 3-dimensional building structure it is shown that the implementation of a Base Control System also yields reduced floor response spectra in a wide frequency range. The same protection systems may also be applied to protect sensitive equipment or machinery against other catastrophic events, i.e. airplane impact. The present contribution is related to the principles of the proposed seismic mitigation strategies and the presentation of numerical analyses and details of executed projects.

## INTRODUCTION

The present paper shall give some ideas to protect nuclear power plant machinery, buildings and equipment against seismic demands. After a short description of the main seismic protection strategies using 3-D Base Control Systems and their principles, some examples for the mentioned three different areas of application are discussed. Beneath the presentation of measured seismic accelerations of two buildings detailed results of seismic analyses are used to provide insight into the seismic mitigation effect of the base control technique.

## SEISMIC PROTECTION STRATEGY

Spring elements with helical steel springs are used worldwide as an elastic support system. The elements are carrying the dead load of the structure and are designed to have sufficient safety margins to bear also additional loads from earthquakes. Additionally to the spring elements highly efficient viscous dampers can be arranged. Figure 1 shows an example for a typical spring and a typical damper device. Due to the arrangement of the springs the system is flexible in the horizontal directions, but possesses also vertical elasticity. The damper supplies absorption forces in the horizontal and vertical directions. The combination of these elements leads to a three dimensional seismic protection system. This system is entitled as Base Control System (BCS) in order to distinguish it from well-known base-isolation systems, where horizontally very flexible and vertically very stiff elements are used.

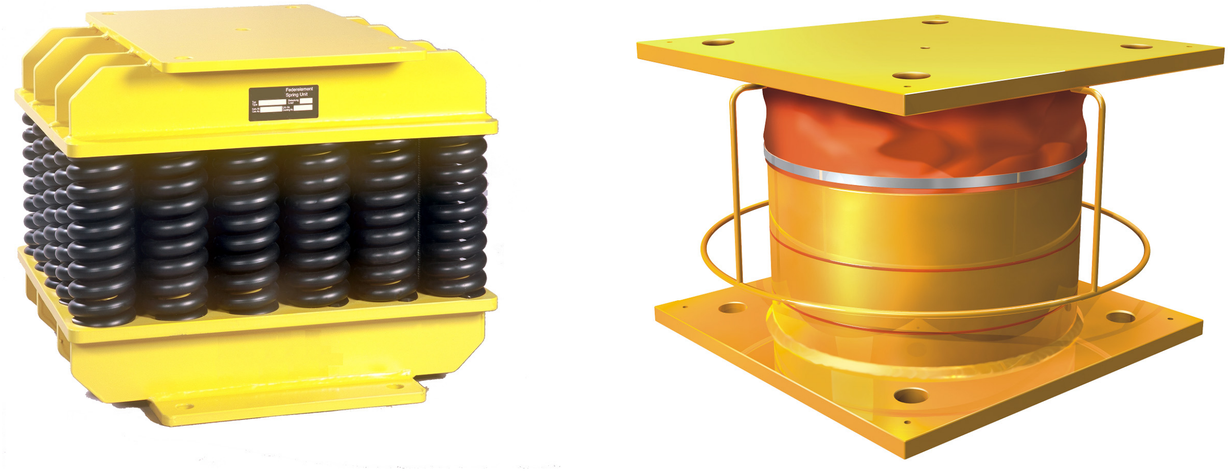

Figure 1. Spring element and viscous damper.

Due to the implementation of spring elements the mode shape of the supported structure is changed and the predominant frequency of the system is reduced (= increase of fundamental period of vibration). The second measure in utilizing this passive seismic control system is based on the increase of damping. The reduction of the induced structural responses by the increase of viscous damping can be taken from different national and international standards. The method of increasing damping may be combined with the reduction of the frequency.

In particular the resulting demands (e.g. accelerations, base shear etc.) of the supported structure can be significantly reduced by using a Base Control System. More details are discussed in the following paragraphs.

## SEISMIC PROTECTION OF MACHINERY

Machinery in power plants can be dynamically decoupled from the substructure by the effective use of elements consisting of helical steel springs and viscous dampers. Turbine foundations, fans, feed pumps, diesel generator sets and other machine foundations benefit from this type of elastic support systems to mitigate the transmission of operational vibration. The application of these devices may also be used to protect the machinery against seismic and other catastrophic events, i.e. airplane crash.

Diesel engines are one example for important machinery in a nuclear power plant. They have the task to supply power for all safety related systems in case of failure of external power. Seismic control strategies for this type of machinery are usually based on the change of the support conditions and corresponding reduction of structural frequencies in combination with an increase of damping. Diesel generator sets can be regarded as somehow “rigid” in the range of seismically significant frequencies. Thus, an elastic layout in horizontal and vertical directions with helical steel springs and additional damper devices can significantly improve the seismic performance of the supported machine.

The following paragraphs present two project examples of diesel engines installed at the nuclear power plant Gösgen. This plant is located in the north of Switzerland close to the village Däniken. It was built by the German supplier Kraftwerks Union (KWU) and is in operation since 1979.

***Bunkered Diesel Generator Set***

After the Fukushima event in 2011 the safety systems of this NPP had to be examined. The bunkered emergency diesel generators represent an important part of the secured safety system. The machinery and its base frame have got a total weight of approximately 12.6 tons. The dimensions of the machine set are about 4 x 2 m in plan and about 3 m in height. Due to the requirement of vibration isolation the system was supported by steel springs since its installation. Kaulbarsch (2013) describes that these existing spring and damper elements were replaced by new combined spring-damper elements during the first shutdown of the plant after the Fukushima event. The main reason was the increase of the safety margin in a seismic case. Figure 2 shows the actual situation.

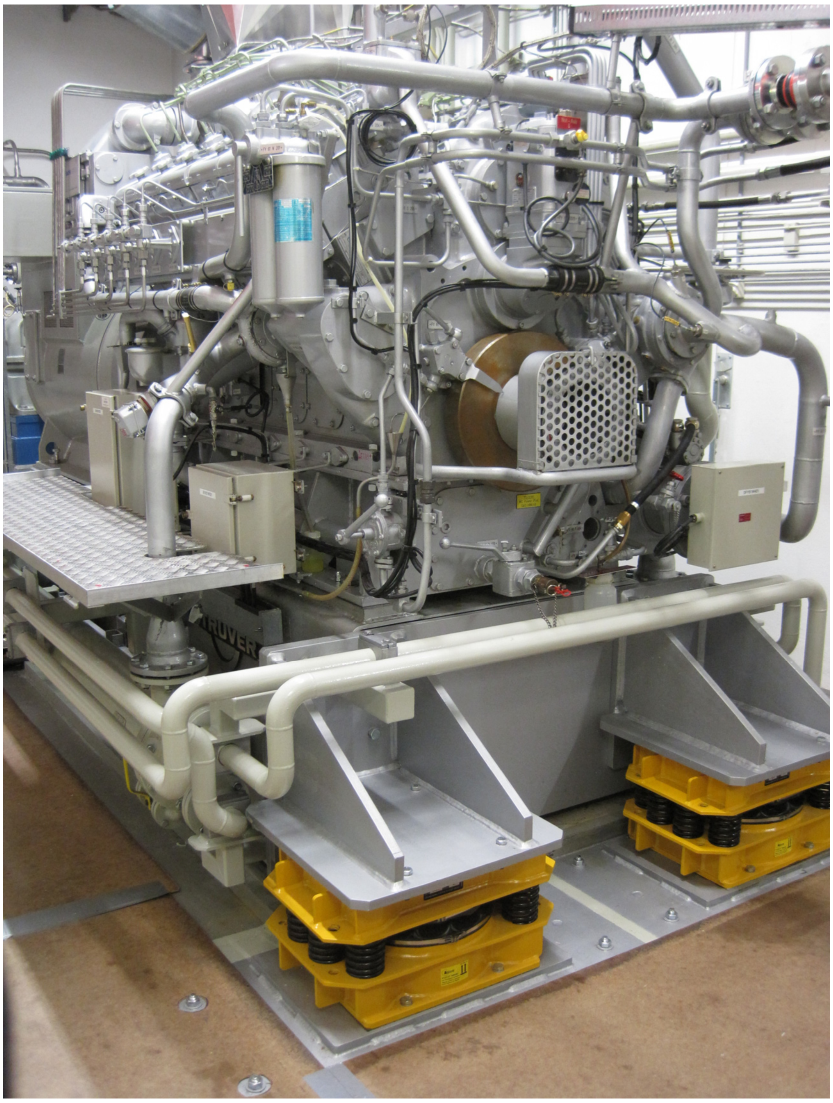

Figure 2. Bunkered emergency diesel set on a Base Control System, NPP Gösgen, Switzerland.

The Base Control System consists of 4 devices, each includes one viscous damper and several helical steel springs. The elements are carrying the dead load of the machinery and its base frame and are designed to have sufficient safety margin to bear also additional loads (in both horizontal and vertical directions) from seismic excitation. The used elements are pre-stressable and allow easy access during inspection and adjustment, if required.

***Emergency Diesel Generator Set***

After 2011 also the emergency diesel engines are reviewed. The existing spring and damper elements below the diesels were replaced by new combined spring-damper elements to increase the safety margin for the loadcase “Earthquake”. Figure 3 presents the elastic supported diesel.

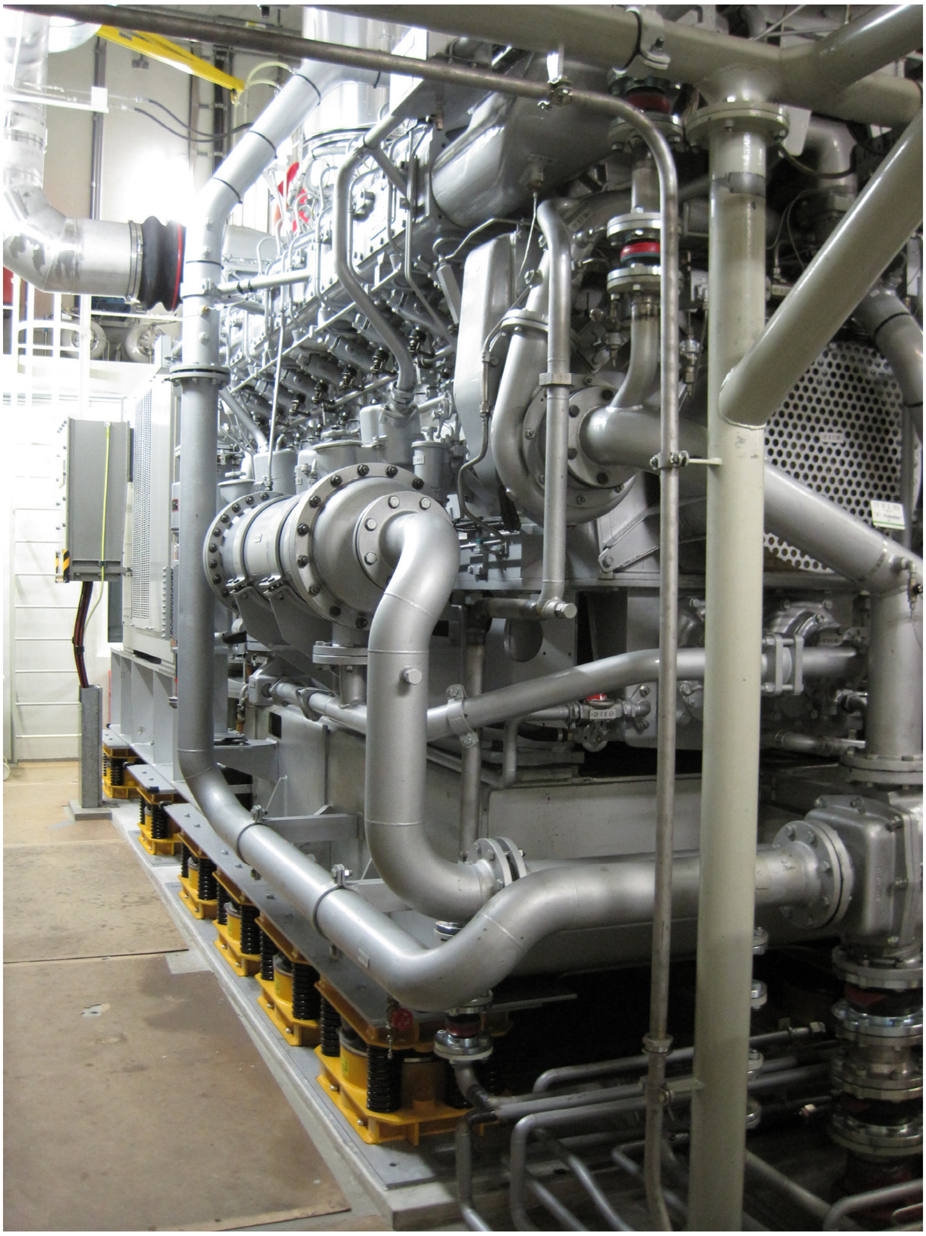

Figure 3. Vibration and seismic control devices for emergency diesel set, NPP Gösgen, Switzerland.

Twelve spring devices support the total weight of about 38 tons. Their vertical flexibility is chosen in regard to provide sufficient vibration isolation efficiency of the machinery. The low horizontal frequencies in range of 1.0 Hz in combination with an increased damping ratio of more than 30 % for the corresponding mode shapes yield an efficient seismic protection. Furthermore, the seismic displacements at the coupling and at the turbo charger connections of the diesel engine were checked to avoid any damage. Finally, an optimum between low frequencies and occurring movements were found.

## SEISMIC PROTECTION OF BUILDINGS

Buildings are elastically supported on elements with helical steel springs to improve noise and vibration protection for several decades. A low vertical frequency of about 3.0 Hz to 5.0 Hz can be used efficiently to reduce vibrations caused by higher excitation frequencies. The structure born noise is significantly minimized. Through an optimal choice of design criteria for the elastic support system the elements can also act as earthquake protection. For this purpose, additional dampers may be arranged or steel springs with a higher ratio between vertical and horizontal stiffness can be used, leading to mode shapes with lower horizontal frequencies. In the optimum case a combination of frequency reduction and increase of structural damping is achieved. The Base Control Systems improve the seismic performance of the buildings significantly. In comparison to base isolation systems, e.g. with rubber bearings, they also work in the vertical direction as there is sufficient vertical flexibility provided by the steel springs.

There are many examples of spring supported buildings worldwide. The following two sections present details of an executed unique apartment project and a case study for the elastic support of a nuclear power plant building.

### *Apartment Building, Mendoza*

Two apartment buildings of the National Technological University of Mendoza were built in 2004 in a seismically prone area at Mendoza, Argentina. Figure 4 shows these buildings. The building on the left side consists of a conventional, “rigid” basement/foundation. The adjacent structure on the right side is supported by a Base Control System consisting of four spring devices and four viscous dampers. Thus, this project is more or less unique, as both structures are nearly identical and will experience the same input in case of a seismic event below the foundation respectively below the Base Control System.

Figure 4. Building with rigid base (left) and supported on a BCS (right).

Both structures consist of three floors of reinforced concrete and masonry infill. The total weight of one building amounts to about 260 tons. The dimensions are approximately 8.2 x 8.7 m in plan with a height of 9 m.

Usually the efficiency of a seismic control system is proven by theoretical analyses before the structure is built. Combinations of experimental and analytical investigations like in Rakicevic et al. (2006) underline the effectiveness of a Base Control System to reduce the seismic demands of a structure. In 2005 it was even possible to measure the seismic response of the base-controlled building at Mendoza in direct comparison to the identical adjacent structure without spring and dampers, as both buildings are permanently equipped with seismic accelerometers. The direct comparison of the two systems under the same seismic event with a peak ground acceleration of about 0.12 g is shown in Stuardi et al. (2008). The reduction of acceleration at the top of the building is significant, at the building with Base Control Systems the acceleration values are reduced by more than 70 %. After adjusting the characteristics of the analysis model due to the measured results it also shows the corresponding reduction factors in regard to internal stress and strain values as well as to the corresponding subsoil reaction loads.

***Base Control System for a Reactor Building***

Parts of buildings (e.g. the main control room) and entire buildings in nuclear power plants have to be protected against possible seismic events. Ryan et al. (2012) illustrates that a typical base isolation system that will lead to an extremely low horizontal stiffness and a high vertical stiffness may lead to horizontal-vertical coupling effects that could amplify the horizontal accelerations. Thus, for the following study the implementation of a Base Control System below the whole reactor building is investigated.

Numerical calculations of a structure, similar to the structure described in Nawrotzki et al. (2013), were performed to assess the reduction effect of the 3-dimensional seismic protection system. For the current study two different finite element models of a nuclear island are prepared using the commercial software SAP2000 from Computers & Structures, Inc. (2014). The nuclear island consists of the containment building and the auxiliary building. The first model, weighing approximately 115,000 tons, consists of fixed restraints at the base mat. The structure is idealized as a 3-dimensional model. The longitudinal axis is the x-axis. The transversal axis is the y-axis and the z-axis is the vertical axis. The second model represents the identical structure, but supported by a control system below the bottom plate. Figure 5 shows the finite element model and some important nodes.

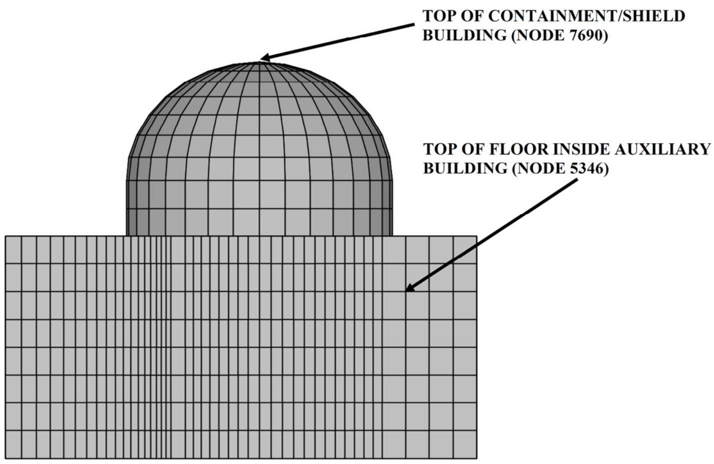


Figure 5. Finite element model of nuclear power plant building.

The fundamental first frequency for the fixed base condition is found to be equal to about 4.0 Hz for both horizontal directions. The elastic support of this structure leads to a modification of the fundamental mode shape. By choosing suitable properties of the springs the frequencies of the modified mode shapes are reduced. The stiffness ratio of the spring is an important parameter during the optimisation process of the elastic support system. Here, a higher ratio between vertical and horizontal stiffness is used, leading to eigenfrequencies in a range between 0.9 Hz and 1.2 Hz for the horizontal mode shapes and a vertical frequency of about 2.5 Hz. Additionally arranged viscous dampers increase the structural damping ratio of the authoritative mode shapes and limit the displacements in the devices.

The seismic analyses of both models have been done for the time domain using a ground acceleration time record with a peak ground acceleration of about 0.35 g. The same input is used for the both horizontal directions. For the vertical direction the input is scaled with a factor of 2/3. The calculation considers a simultaneous excitation in all three directions. Figure 6 shows the accelerogram and the corresponding 5 % damped acceleration response spectrum.

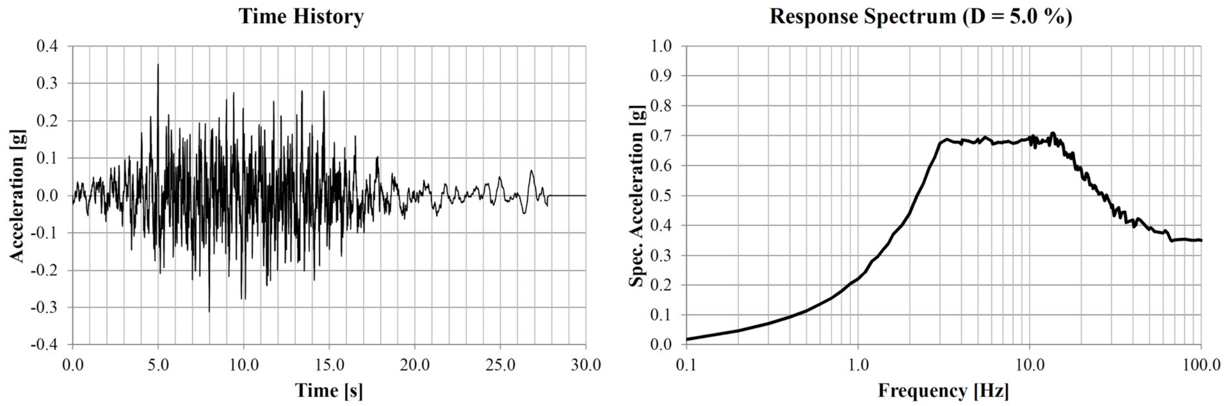


Figure 6. Time record and 5%-damped spectrum of the applied horizontal earthquake.

Linear modal time history analyses were performed using the shown time history as base excitation at the restrained nodes below the structure respectively below the support devices. The total horizontal base shear can be reduced by more than 70.0 % and the vertical forces can be reduced by more than 10.0 % if the structure is base controlled. Time history data of the floor accelerations in all three spatial directions were calculated at each chosen location within the building. Afterwards these results were processed with SAP2000 to generate in-structural response spectra, automatically considering a frequency widening of 15.0 %. The results are similar for both horizontal directions, thus Figure 7 shows the floor response spectra in one horizontal direction and in the vertical direction.

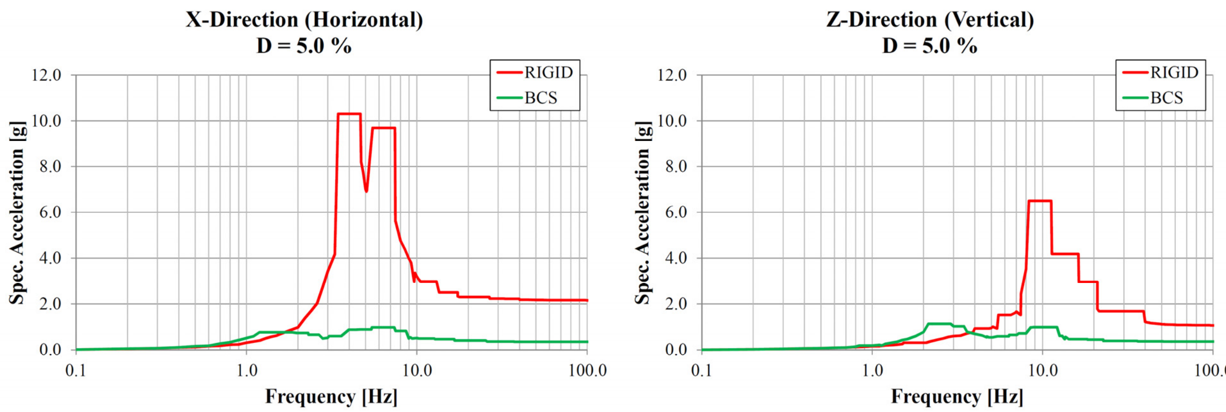


Figure 7. Efficiency of the BCS in horizontal and vertical directions.

The red curves (“RIGID”) represent the spectra of the building with fixed restraints, and the green curves (“BCS”) are the spectra of the building with Base Control System. Due to the arrangement of the seismic protection system the dominated frequencies are shifted to a lower frequency band compared with the one without BCS. The responses inside the facility are significantly mitigated. The spectra for the structure with BCS show discrete peaks for frequencies of approximately 1.2 Hz (horizontal direction) and about

2.5 Hz (vertical direction) due to the natural frequencies of the system. These small and narrow peaks are unavoidable but they do not occur in the area of concern for most equipment and machinery. The spectral acceleration values for the protected structure are significant lower than the values of the unprotected building in a wide frequency range. It should be noted that floor response spectra can only be used for such components, equipment and structures, whose masses do not significantly affect the vibrational behaviour of the building. More detailed coupled finite-element models are required for all other cases.

The induced seismic accelerations and the base shear values are significantly reduced if a Base Control System is applied. Based on these results it can be concluded that even the internal forces and stresses can be reduced in a same order of magnitude. Furthermore, it is also important to have a look at the occurring displacements. Small values of internal relative displacements are expected, as the structure itself is very massive and rigid. Only the relative displacement between building and vicinity is of particular importance. Thus, the corresponding connections, e.g. steam pipe systems, have to be designed to withstand such relative motion.

## SEISMIC PROTECTION OF EQUIPMENT

In nuclear power plants many sensitive items of equipment shall be protected against seismic actions. The experience in earthquake protection of machinery and buildings can be applied to control structures which originally do not require vibration isolation. Equipment in (nuclear) power plants can be supported by helical steel springs and viscous dampers exclusively against seismic input and/or airplane crash. These structures often consist of sensitive material or the safety is of particular interest.

Spent fuel pools in nuclear power plants are one example of sensitive equipment. They require special attention in regard to safety. Structural acceleration should be kept to low values as the overflow of liquid is not acceptable and the integrated steel enclosures should not contact each other. Here, water leakage and subsequent release of radioactive substances must be avoided. Base-control systems may also be used for the seismic protection of these structures. The main purpose here is not related to the reduction of structural stresses or strain, but to the reduction of response acceleration. Waves on the water surface should not overflow the top of the pool walls. Figure 8 shows a Base Control System consisting of helical steel spring elements and spring-viscodamper combinations on which a whole fuel pool, weighting approximately 6000 tons, is resting. The special characteristics of the support devices lead to relatively low structural frequencies and correspondingly high damping which reduces acceleration and avoids the overflow of water.

Figure 8. Seismic control system below spent fuel tank in a high seismic zone.

Base Control Systems for improving the dynamic behaviour can be used not only for large and heavy equipment like the spent fuel storage tank, discussed in Nawrotzki (2009), but also for small and light equipment. As an example hereafter an electrical cabinet with dimension of about 2.8 x 1.5 m in plan and about 2.4 m in height is investigated. The structure with a weight of approximately 2.5 tons is installed on an upper floor in the nuclear power plant building, described in the previous chapter. Thus, the calculated acceleration time histories inside the building could be used as base excitation for the electrical cabinet. Here, the results of the building without protection system are used.

The system is idealized as a 3-dimensional finite element model consisting of solid elements. For the model with fixed restraints the first horizontal natural frequency (bending mode shape) amounts to about 14.5 Hz. The model is excited by three acceleration time histories, acting in all three spatial directions. Subsequently, the identical model is placed on a Base Control System.

The parameters of the steel springs are chosen so that the first horizontal mode shape in the longitudinal direction and the first horizontal mode shape in transverse direction are in the frequency range between 1.0 Hz and 1.4 Hz. The vertical eigenfrequency is found to be about 2.4 Hz. The dampers are optimized to reach a modal damping of more than 20 % for the horizontal natural frequencies and a damping ratio of more than 10 % for the vertical frequency. The finite element model with springs and dampers is shown in Figure 9.

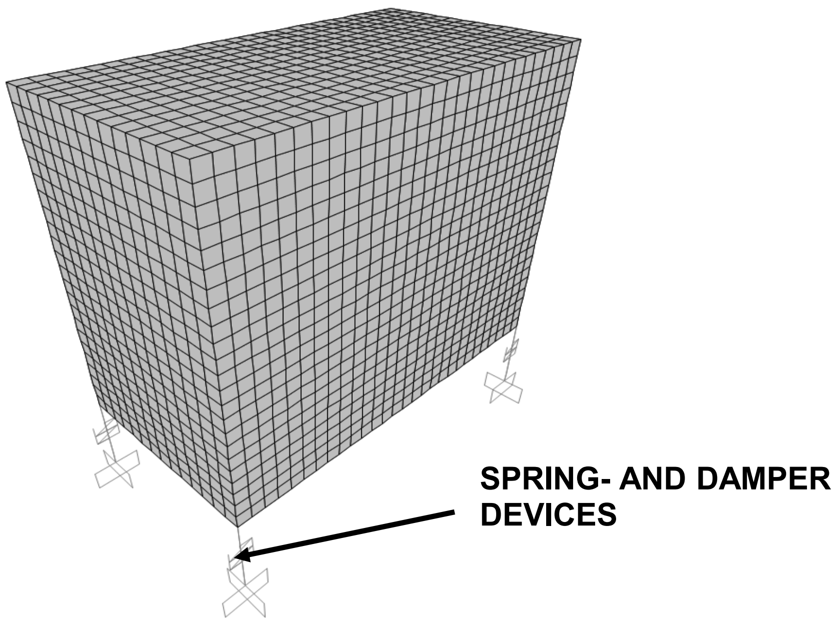


Figure 9. Finite element model of electrical cabinet.

A comparison of the calculation results of the two models shows that the maximum absolute acceleration can be reduced at the top of the electrical cabinet by more than 50% in the horizontal and in the vertical directions when the Base Control System is applied.

Sensitive small components inside the control cabinet can be designed according to an analogous procedure to the calculation of floor response spectra of a building structure. At the centre of gravity inside the finite element model the occurring acceleration time histories are calculated and SAP2000 generates the corresponding response spectra. Figure 10 shows one example for these in-structural response spectra for both models.

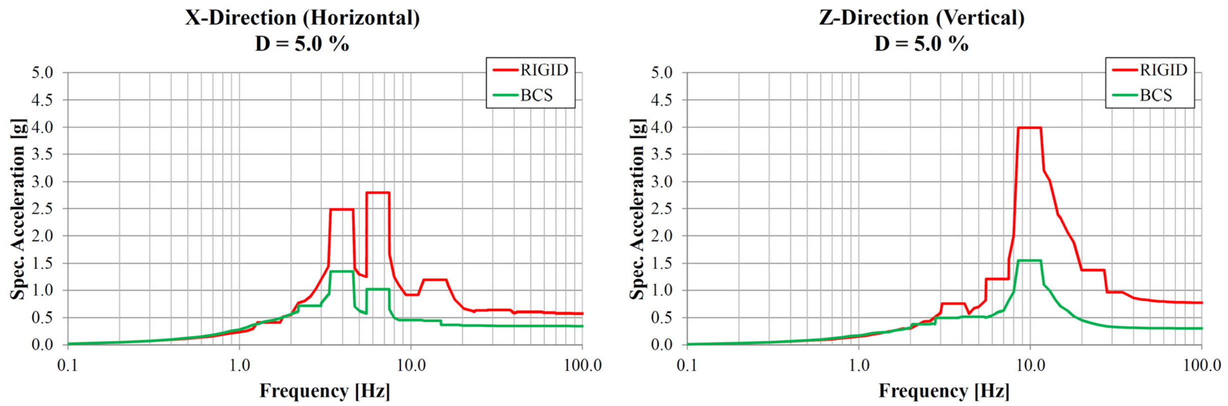


Figure 10. Comparison of in-structural response spectra evaluated at centre of gravity.

The red curves (“RIGID”) represent the spectra at the structure with fixed restraints, and the green curves (“BCS”) are the spectra of the cabinet with Base Control System. The comparison of the spectra for the system without BCS and with BCS shows the effectiveness of the protection system nearly in the whole frequency range.

## CONCLUSION

After a brief outline of the fundamentals of Base Control Systems and the corresponding seismic protection strategies, several examples for the elastic support of machinery, buildings and equipment are discussed. Calculated and measured seismic responses show that the proposed control system leads to a significant reduction of accelerations, base reactions and spectral values of floor response spectra.

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