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OPTIMISATION OF 3-D BASE CONTROL SYSTEMS FOR THE SEISMIC PROTECTION OF POWER PLANT MACHINERY, EQUIPMENT AND BUILDINGS

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ABSTRACT

Machinery, floors, entire buildings, electrical cabinets and other sensitive equipment in power plants have to be protected against seismic excitations. Elements that consist of helical steel springs and viscous dampers are traditionally used for the elastic support of these structures to achieve vibration isolation. Optimising the parameters of these devices leads to a Base Control System (BCS), an efficient passive seismic protection system. As the spring elements provide flexibility in both horizontal as well as in vertical direction and the dampers generate damping forces in all three spatial directions the BCS represents a 3-dimensional mitigation system. Supporting a structure on a BCS yields significantly reduced seismic acceleration levels, internal stresses and floor response spectra. This contribution presents strategies for enhancing the layout parameters of the Base Control Systems. It is possible to adjust the properties of the BCS in regard to the requirements of the specific project, as the elements vary especially in the bearing capacity, in the horizontal and vertical stiffness properties, in the ratio between horizontal and vertical stiffness and in the damping resistance. Details of several executed projects and corresponding results of numerical investigations document the effectiveness of the presented seismic protection strategies. Selected pictures are used to illustrate the general applicability of the mitigation system.

INTRODUCTION

The aim of this technical paper is to inform the reader about some ideas to protect nuclear power plant machinery, equipment and buildings against seismic demands. After a short description of the basics of 3-D Base Control Systems (BCS), some options for their optimisation are presented. Details of executed projects and results of numerical investigations document the effectiveness of the control system.

The BCS consists of spring elements that are carrying the dead load of the supported structure and are designed to have sufficient safety margin to bear also additional loads from seismic and other excitations. They consist of helical steel springs which possess linear-elastic behaviour in both horizontal and vertical directions. The system is flexible in the horizontal directions, but yields also vertical elasticity. Viscous dampers, arranged in parallel to the spring devices, provide linearly velocity-dependent forces in all three spatial directions. Arranging these devices below a structure leads to a Base Control System. The chosen designation is used to distinguish this 3-dimensional support system from well-known base isolation systems, where horizontally very flexible and vertically very stiff devices are used.

Due to the application of flexible spring devices the mode shape of the structure is changed and it is possible to reduce the predominant frequency of the system. The implementation of dampers leads to an increase of structural damping and these devices reduce the relative displacements of the supported structure and of the devices themselves. The combination of reduced frequencies and increasing damping yields efficient seismic protection of a structure in all three directions. Absolute accelerations and hence internal forces are reduced. These positive effects are verified by theoretical and experimental investigations, as presented by Rakicevic et al. (2006).

In case of typical base isolation systems the extremely low horizontal stiffness and a high vertical stiffness may lead to horizontal-vertical coupling effects which could amplify the horizontal accelerations inside the structure, see Ryan et al. (2012). For a base controlled structure there are no effects on higher modes. Furthermore, the vertical flexibility could be used to provide vibration isolation for machinery or buildings. At the same time the devices of a BCS yield also a protection against shock loads, like airplane crash. Figure 1 shows the typical arrangement of a BCS below a structure.

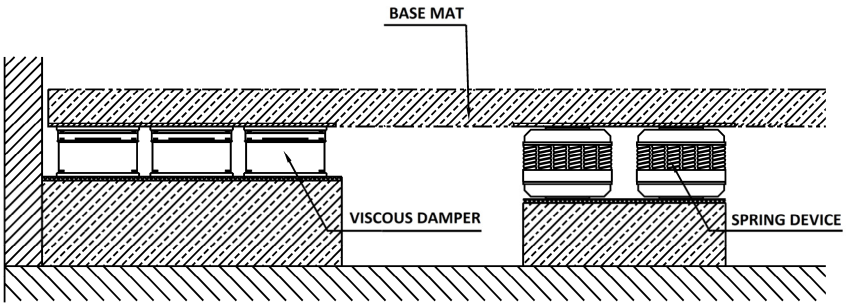

Figure 1. Base Control System below a building.

The parameters of the devices do not change over time. There are no aging effects. As the elements consist of steel parts regular visible inspections are recommended. The access to the devices is quite easy, allowing for inspection, adjustment and exchange, if required.

OPTIMISATION POSSIBILITIES

The elements of a Base Control System vary especially in the bearing capacity, in the horizontal and vertical stiffness properties, in the ratio between vertical and horizontal stiffness (Kv/Kh) and in the damping. One of the most important optimisation criteria of the 3-dimensional support system is the stiffness ratio Kv/Kh. Herewith the mode shape of the structure can be controlled. Using a low value could lead to a horizontal mode shape including a large rocking part. The increase of Kv/Kh yields a mode shape with less rocking. Typical values used successfully for this ratio are found in a range between 5 and 8. Now the horizontally soft springs also reduce the system frequency and the induced seismic accelerations. Thus, the stiffness ratio helps to control the mode shapes and to reduce seismic demands.
An important effect is that lower frequencies cause larger displacements. This has to be considered regarding the differential displacements between supported structure and adjacent structures; hence also in the surface of the devices. A simplified single degree of freedom system with a damping ratio of 5 % is used as a corresponding example. The seismic input is defined by a randomly chosen design response spectrum according to ASCE/SEI 7-10 (2010), see left side of Figure 2. The calculated relationship between seismic acceleration and displacement can be seen on the right side of Figure 2.

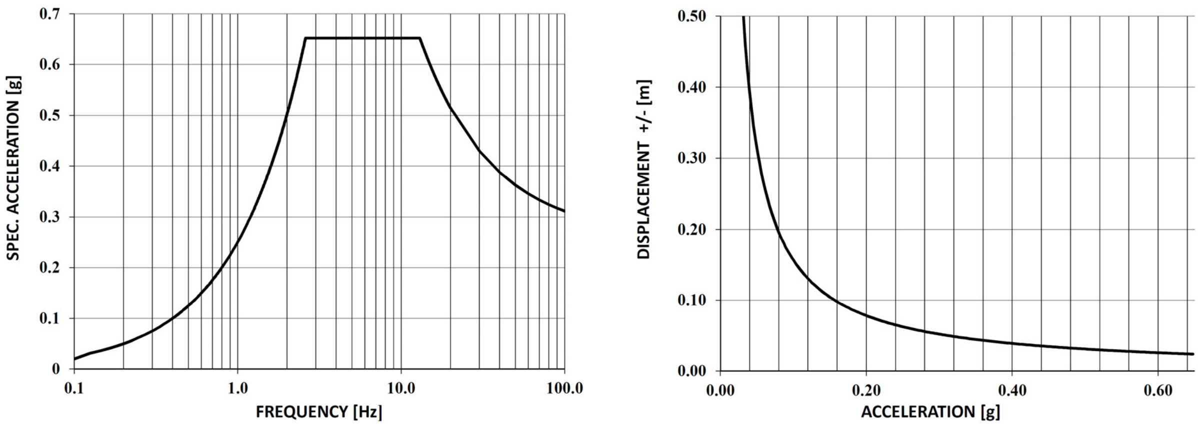

Figure 2. 5 % damped spectrum (left) and relation between displacement and acceleration (right).

This figure underlines the requirement of finding an optimum between the reduction of accelerations and occurring displacements. In general it is not recommended to yield extremely low accelerations with enormous relative displacements. It would be better to use a different support strategy – with a little bit higher accelerations but in combination with an increase of damping to control the displacements. The strategy should always focus on the project specific requirements, e.g. in terms of an acceleration limit.

PROTECTION OF MACHINERY

The elastic support of machinery has become "state of the art" to achieve efficient vibration isolation. In a NPP elements with helical steel springs are typically installed below turbo generator sets, feed water pumps, fans, emergency diesel generators and other machine foundations. Figure 3 shows the typical view of spring support devices below turbine decks.

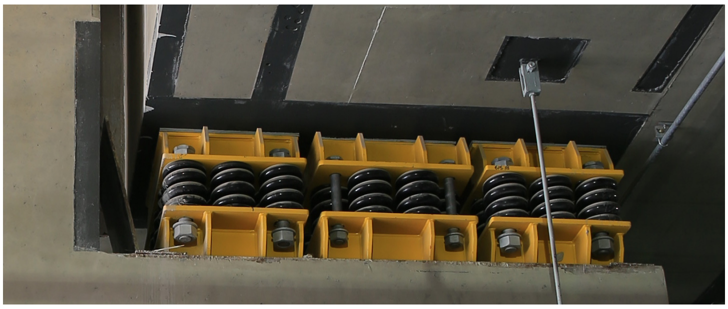

Figure 3. Elastic devices below turbine foundation.

In many cases the applied devices may also be used to protect the structures against seismic and other extraordinary load cases. The following section presents the design of a large turbine foundation in a seismic area.
Two new 500 MW turbine units from BHEL (Bharat Heavy Electricals Ltd.) were installed during the extension of the existing thermal power station Anpara in Uttar Pradesh, India. The site is located in a high seismic zone with a peak ground acceleration of 0.22 g. During the layout of the turbine deck the seismic behaviour of a conventional, rigidly supported turbine deck was compared with the behaviour of a spring supported T/G-deck. The calculations used a three-dimensional finite element model of the structure, as shown in Figure 4.

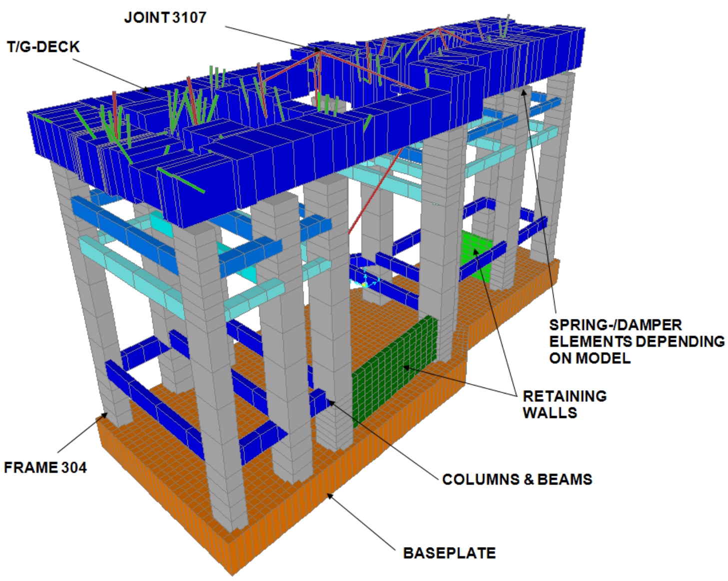

Figure 4. Finite element model of spring supported foundation.

This model consists of the turbine deck, the spring devices and the substructure. The parameters of the spring and damper devices were chosen during an optimisation process. Finally, three different systems are investigated: System without spring devices, System with spring devices type 1 and System with spring devices type 2.

The system without devices shows a first horizontal mode shape in transversal direction with a frequency of about 2.0 Hz. Implementing the first type of spring devices leads to a reduced eigenfrequency of about 1.1 Hz with a damping ratio of 10 %. Together with the change of the mode shape this seismic protection strategy could reduce the induced seismic demands from 0.57 g down to about 0.27 g.

The properties of the support devices are optimised in a second step. Using a higher ratio between vertical and horizontal stiffness in combination with an increase of damping yields a frequency of about 1 Hz with a damping ratio of 15 %. This layout leads to a further reduction of spectral acceleration to about 0.2 g. A similar efficiency can be found for the longitudinal direction.

Response spectrum analyses are performed to verify the protection strategy. Table 1 shows some important results. The values of the model without elastic devices are used as reference values (100 %).

Table 1: Comparison of response spectrum analyses.

Excitation in transverse direction	Without elastic support	Springs type 1	Springs type 2
Abs. acceleration at shaft level (Node 3107)	100 %	55 %	41 %
Bending moment at column (Frame 304)	100 %	69 %	48 %
Shear force at column (Frame 304)	100 %	50 %	34 %

The absolute acceleration values as well as internal forces are significantly reduced. Due to the positive effects the spring devices type 2 are finally applied as vibration isolation system (VIS) and seismic protection measure for this project. The seismic behaviour of the conventional foundation and the system with VIS can be seen also in Figure 5.

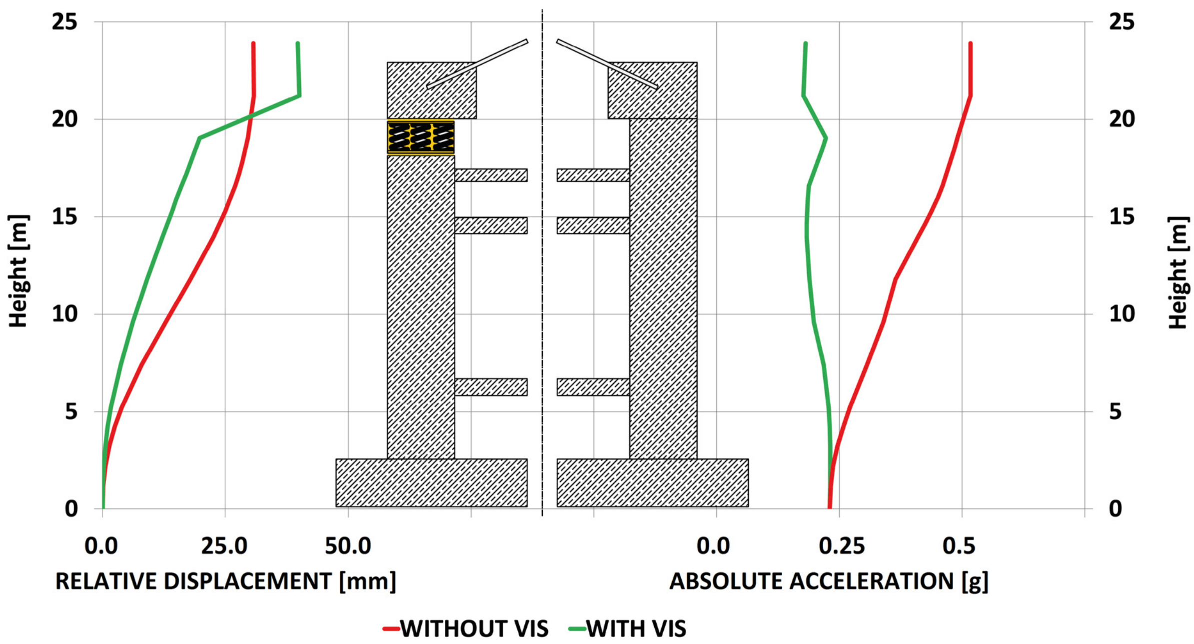

Figure 5. Comparison of relative displacements (left) and absolute accelerations (right).

Due to the optimised parameters of the spring and damper devices there is nearly no amplification of the acceleration over the height of the structure. At the system without elastic support the accelerations are amplified with a factor up to 2.3, regarding the peak ground acceleration. Another positive effect of the optimised devices is that the displacements are still in the same order of magnitude as for the unprotected structure.
For this project the direct substructure below the VIS was not integrated into the adjacent structure of the machine house. Figure 6 shows a possible layout using this integration method.

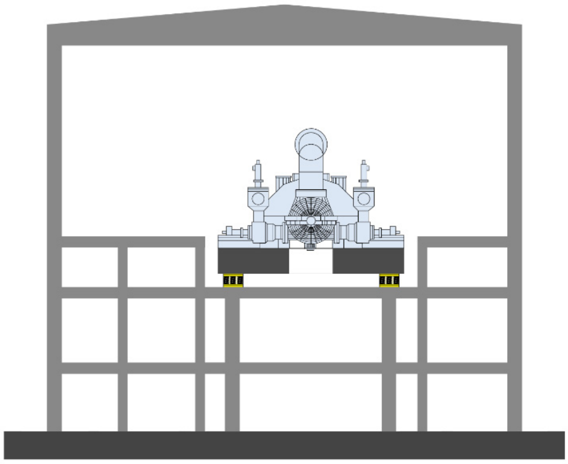

Figure 6. Optimised machine building with integrated T/G-deck on elastic support system.

This type of layout, used more and more worldwide, provides several further advantages as described in Basu et al. (2011). The seismic behaviour in terms of relative displacements between structures, induced acceleration at the shaft level and induced structural stresses and soil pressure is improved. It is also possible to save space and construction time; thus additional economic advantages arise.

PROTECTION OF EQUIPMENT

Spring elements and viscous dampers are implemented to achieve vibration isolation and seismic protection of important machinery, as described in the previous chapter. The same or similar devices can be used to control structures which originally do not require vibration isolation, but should be protected against random or shock vibrations due to earthquakes and/or airplane crash. Spent fuel storage tanks, switchboards or electrical cabinets are typical examples of sensitive equipment in a NPP. Figure 7 shows the typical arrangement of a Base Control System below a structure and a simplified finite element model of a cabinet.

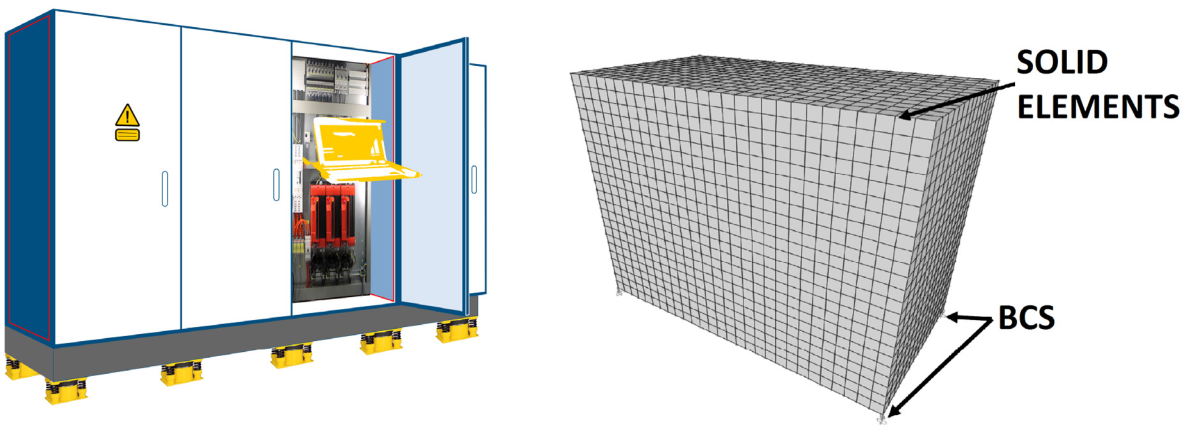

Figure 7. BCS below cabinet and finite element model of an electrical cabinet.

The finite element model represents a structure with dimensions of about 1.5 x 2.8 m in plan and a height of about 2.4 m. The weight amounts to approximately 2.5 metric tons. The properties of the BCS devices are optimised to reach low horizontal mode shapes (rigid body modes) within a frequency range between 1.0 and 1.4 Hz in combination with an increased damping ratio. The vertical eigenfrequency was chosen to about 2.4 Hz. The numerical investigations of the structure has been done for the time domain using different acceleration time records, to simulate the seismic input as well as the input due to airplane crash. The corresponding response spectra are shown as dashed lines in Figure 8. For one horizontal direction, as the results of the two horizontal directions are very similar, and for the vertical direction the response spectra at top of the BCS are calculated, considering a frequency widening of ±15 %. These curves are shown as solid lines in comparison to the spectra below the devices in Figure 8.

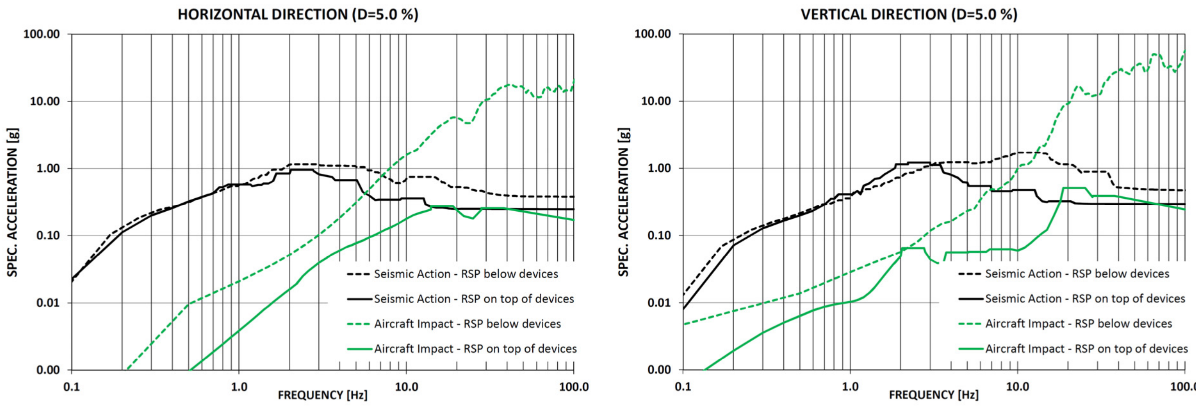

Figure 8. Comparison of response spectra below and on top of the devices.

The comparison of the response spectra of input and output shows that the maximum absolute accelerations are significantly reduced for both load cases. Regarding the high frequency content of the airplane impact the filtering effect of the elastic support becomes obvious. The responses spectra on top of the BCS are lower than the spectra below the support system in the complete frequency range for the shock loading. For the seismic case there exist some small exceedances of the input spectra due to the unavoidable natural frequencies of the elastically supported structure. This can be seen for example in the plot of the vertical spectra due to the seismic case. At the frequency area around 2.4 Hz the solid line is slightly higher than the corresponding dashed line. Thus, for smaller components inside the cabinet the relevant frequencies should not be in the range of the natural frequencies of the spring supported system. For a wide frequency range the spectral values are also reduced during seismic excitation.
More details about this example structure can be found in Siepe and Nawrotzki (2015). Here also the comparison between the base controlled cabinet and a cabinet without mitigation system is discussed. Apart from the small narrow area around the eigenfrequencies of the elastically supported structure, the BCS yields significantly reduced acceleration values in a wide frequency range compared to the unprotected structure.

PROTECTION OF BUILDINGS

Entire buildings or part of buildings in nuclear power plants have to be protected against possible seismic events. So far, there are more than 100 buildings worldwide nowadays 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. if there is a train passing very closely. The high-frequency excitation in vertical direction, which may disturb or endanger the structure, is filtered out by low frequency support systems. In seismic areas this support strategy is modified to consider also the effects of earthquakes. Viscous dampers are arranged in parallel to the spring devices to increase the damping. The stiffness parameters are adjusted to achieve a higher ratio between vertical and horizontal stiffness, as described in a previous chapter. Nawrotzki et al. (2013) presents the measured

results of a corresponding project example. Two identical apartment buildings are built in Mendoza, Argentina. The first structure is supported on a conventional foundation; the second one is supported on a BCS. During a seismic event in 2005 the results of the seismic accelerometers verify a significant reduction of absolute accelerations at the base controlled building in a range of more than 70 % compared to the rigidly supported building.
Thus, it seems absolutely possible to install the whole nuclear island on top of a Base Control System, see Figure 9.

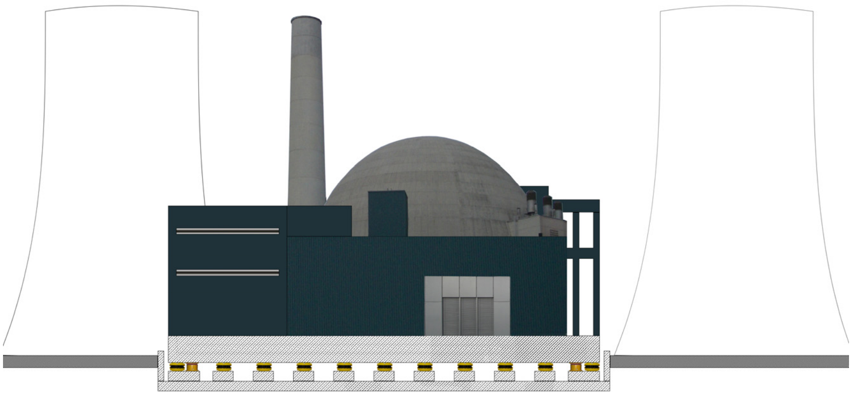

Figure 9. Base Control System below NPP building.

In this case the resulting seismic accelerations and internal forces inside the building will be relatively small. Due to the parameters of the BCS small values of internal relative displacements are expected. The relative displacements between building and vicinity are more important, as corresponding connections like steam pipe systems have to be designed for such relative motion.
Numerical investigations of a NPP building structure, weighting approximately 150.000 metric tons, are performed to assess the reduction effect of a 3-D Base Control System. For this feasibility study two different finite element models, similar to the structure shown in Figure 9, are prepared. One model consists of fixed restraints at the base mat. The other model considers the identical structure supported on a BCS. The longitudinal axis is the x-axis. The transversal axis is the y-axis and the z-axis represents the vertical axis. The seismic analysis has been done for the time domain using a ground acceleration time record shown in Figure 10. The calculations consider a simultaneous excitation in all three directions. The same input was used for the horizontal and vertical directions as a simplified assumption.

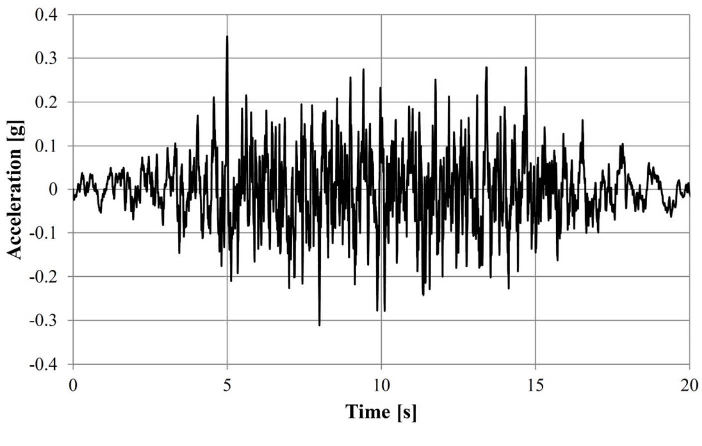

Figure 10. Time history with a peak ground acceleration of 0.36 g (PGA).

The maximum results in terms of base shear and absolute acceleration at the roof of the structure are evaluated. Figure 11 shows that the BCS yields a reduction of base shear and accelerations by more than 75 %. As the system also works in the vertical direction, there is also a significant reduction effect.

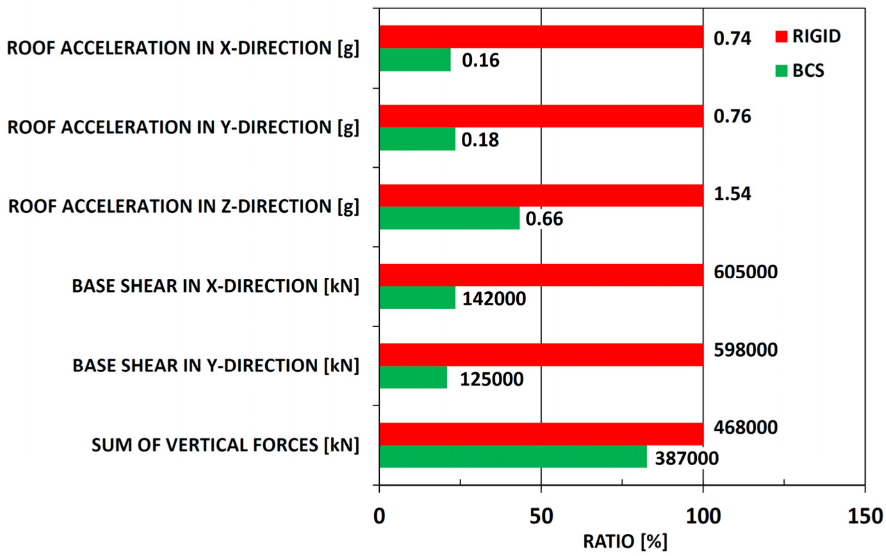

Figure 11. Comparison of time history analyses.

Based on these results it can be concluded that even the internal stress and strain values will be reduced in a same order of magnitude. In comparison to base isolated structure, with a very low horizontal frequency, there are smaller relative displacements in the devices of a BCS. Beneath the displacements also the interstorey drift values play an important role. First the horizontal displacements u_i of the i-th storey are calculated. The variable h_i is the i-th storey height. Than the harmful interstorey drift angle θ_i is calculated according to Equation 1 using the improved secant method described in Zhou et al. (2012).

$$\Theta_i = \frac{u_i - u_{i-1}}{h_i} - \frac{u_{i-1} - u_{i-2}}{h_{i-1}} \tag{1}$$

Figure 12 shows the comparison of the relative displacements and drift angle of the base controlled building and the rigid base structure.

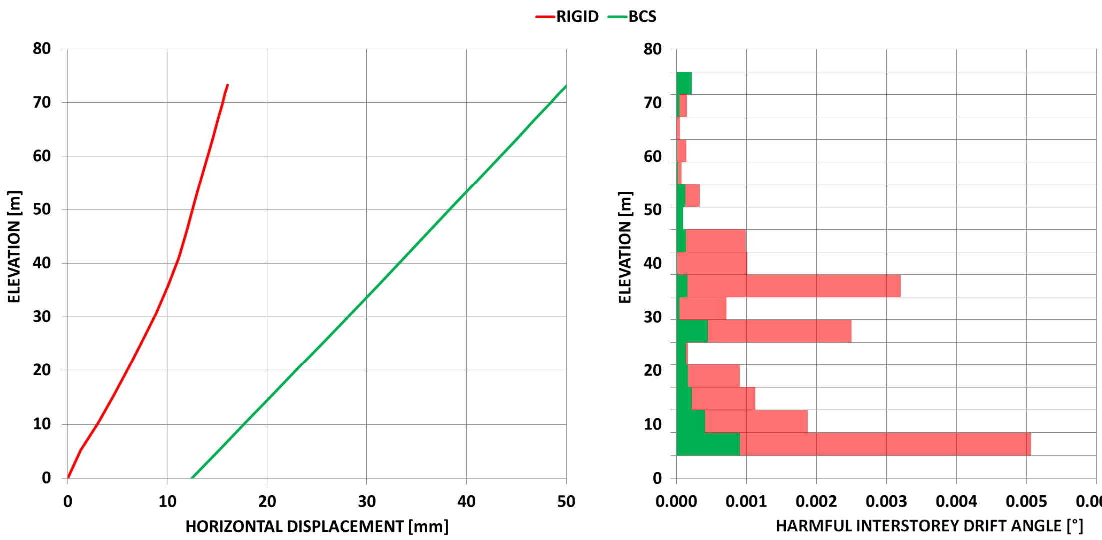

Figure 12. Comparison of displacements and harmful interstorey drift angle.

It is important to mention that even the displacements at the top of the structure with BCS are quite small, less than 5 cm. The horizontal interstorey drift ratios are in favour of the BCS as it behaves nearly like a rigid body structure.
Furthermore, it is also important to have a look at the in-structural response spectra, typically used for the layout and design of equipment inside the building. Figure 13 shows the floor response spectra at a higher elevation of the structure. In one case ("RIGID") the building is supported by fixed restraints; in the second case ("BCS") the structure is supported by a BCS.

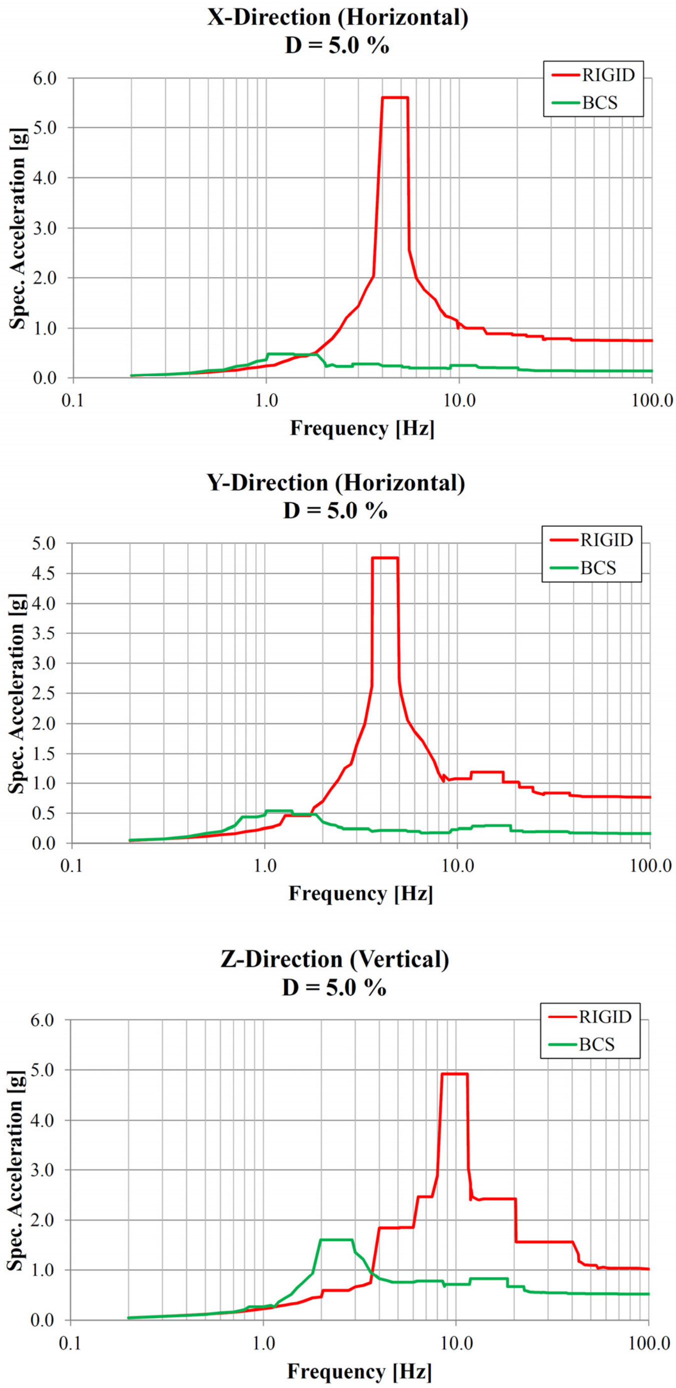

Figure 13. 3-dimensional efficiency of BCS.

All curves of Figure 13 consider a frequency widening of ±15 %. The green curves of the BCS shows small narrow peaks around 1.1 Hz for the two horizontal directions and around 2.5 Hz in the vertical

direction. This effect is unavoidable because these frequencies represent the authoritative eigenfrequencies of the elastically supported system. Above these frequencies the floor response spectra of the building with BCS are significantly lower than the spectra of the unprotected building. This efficiency provides an important advantage for the design and behaviour of the equipment. Using different sets of time histories similar results are found for another NPP structure, as described in Nawrotzki and Siepe (2014).
Due to the presented results it can be summarized that the arrangement of a Base Control System leads to a significant reduction of the absolute accelerations, base reactions and spectral values of the floor response spectra in a wide frequency range.

CONCLUSION

An approach for the optimisation of 3-D Base Control Systems for the seismic protection of power plant equipment, machinery and buildings was investigated and has shown its effectiveness and potential application. After a short introduction into the basics of Base Control Systems and corresponding optimisation possibilities, some project examples were discussed.
It is shown that the proposed control system leads to a significant reduction of accelerations, internal stresses, base reactions and the values of the in-structural response spectra.

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