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3-D SUPPORT SYSTEMS FOR THE SEISMIC CONTROL OF NPP STRUCTURES

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ABSTRACT

At present, it seems that more and more Nuclear Power Plants are under construction or will be constructed in areas of high seismicity. For countries such as Turkey, Bangladesh, or even regions in the south of France, earthquake risk certainly plays a very important role. In addition to high PGA values of more than 0.3 g, subsoil conditions are also not optimal at certain locations. Thus, relatively soft soils or soils sensitive to uneven settlements are additional challenges. This article illustrates the application of 3-dimensional support systems for the earthquake protection of NPP structures. A step-by-step description of the layout process for a 3-d system is first provided. Subsequently, the application of these steps to the layout of a Base Control System is explained using project examples. Details of these projects and corresponding results of numerical investigations document the effectiveness of the presented seismic protection strategies. Due to its vertical flexibility and the possibility to use pre-stressable spring elements the proposed system provides the possibility of adjusting the building height during the entire lifetime and can easily and reliably compensate all uneven soil settlements that could happen during the structures long-term operation. Selected pictures are used to illustrate the general applicability of the mitigation system. Furthermore, some general recommendations regarding the parameters of these systems are given. As the devices of the system 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, a certain optimisation process is required. In addition, typical parameters are provided in tabular form to have appropriate starting values.

INTRODUCTION

The most common seismic isolation systems, like lead rubber bearings, rubber pads and friction pendulum systems are effective only for protection against horizontal earthquake excitation. The corresponding devices provide a large stiffness in vertical direction and yield an entire transmission of the vertical earthquake component into the supported structure. Furthermore, the corresponding coupling phenomenon of horizontal and vertical components could amplify the horizontal accelerations in higher frequency modes, as presented in Ryan et al. (2012). Therefore, the demand and requirement regarding three-dimensional seismic control of important structures is increasing significantly.

In literature several examples of 3-D base isolation systems can be found, typically consisting of combinations of 2-D devices with vertical 1-D devices. IAEA (2020) describes additionally a different approach: systems with helical steel springs and viscous dampers. These systems provide flexibility in horizontal and vertical directions and damping forces in all spatial directions. The corresponding 3-dimensional support systems are frequently used to reduce seismic demands. At the same time these systems yield vibration isolation efficiency as well as protection against other catastrophic events, such as aircraft impact or shock loads. It is shown in Nawrotzki et al. (2013) that these systems lead to a significant reduction of accelerations, internal stresses, soil reactions and the values of the in-structural response spectra. Machinery (e.g. Turbo-generator Sets, Emergency Diesel Generators, etc.), equipment (e.g. spent fuel storage tank) in nuclear power plants already benefit from the mentioned advantages. Also outside the NPP sector, there are several examples of base-controlled structures.

Based on the previously mentioned experience it is no longer unthinkable that a complete nuclear island structure will be supported by a 3-d support system, as illustrated in Figure 1. This concept is supported in the meantime by newer test methods, allowing a full-scale testing of devices subjected to full dead load and seismic displacement, as described in Nawrotzki et al. (2019).

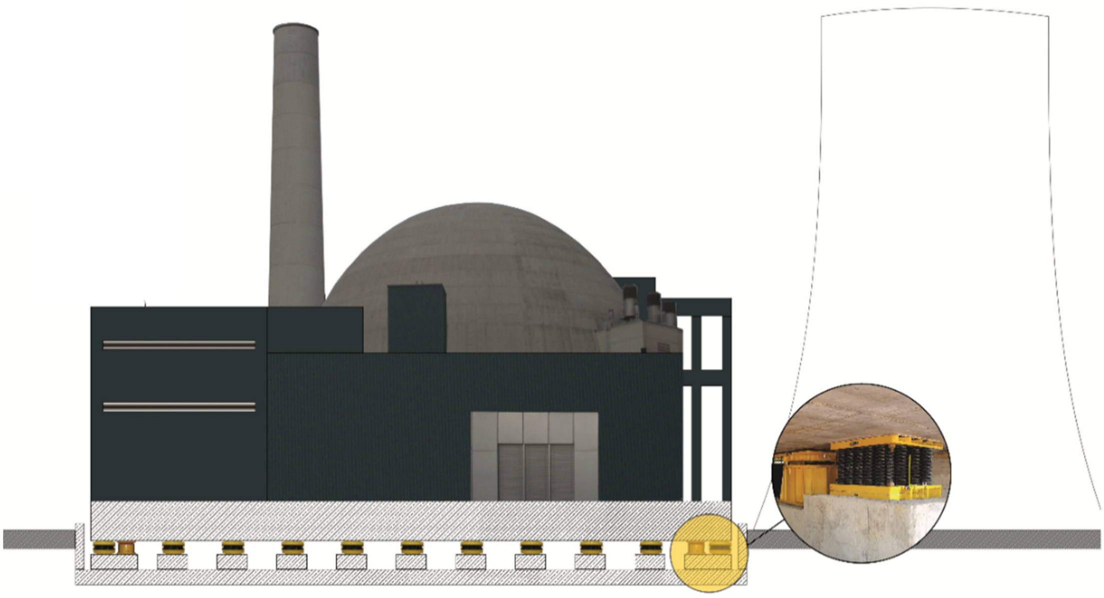

Figure 1. 3-D Base Control System below NPP building.

This paper presents basic layout criteria and efficiency analysis for the 3-D support system for typical NPP structures. Details of corresponding executed projects are presented to illustrate the theoretical investigations.

LAYOUT PRINCIPLES

The layout of a suitable seismic mitigation system requires experience from the responsible designer. This section describes the corresponding procedure for a Base Control System (BCS) as an example. A BCS systems consist of spring elements, which are arranged underneath the base plate of the structure. Highly efficient viscous dampers are arranged in parallel to the elastic support devices. The system is flexible in both horizontal directions, but possesses also vertical elasticity. The dampers supply damping forces in all spatial directions. Due to the implementation of spring elements the mode shape of the structure is changed and the predominant frequency of the system is reduced (=increase of fundamental period of vibration). The arrangement of dampers yields a significant damping ratio of the important mode shapes. A typical view of such a system is shown in Figure 1.

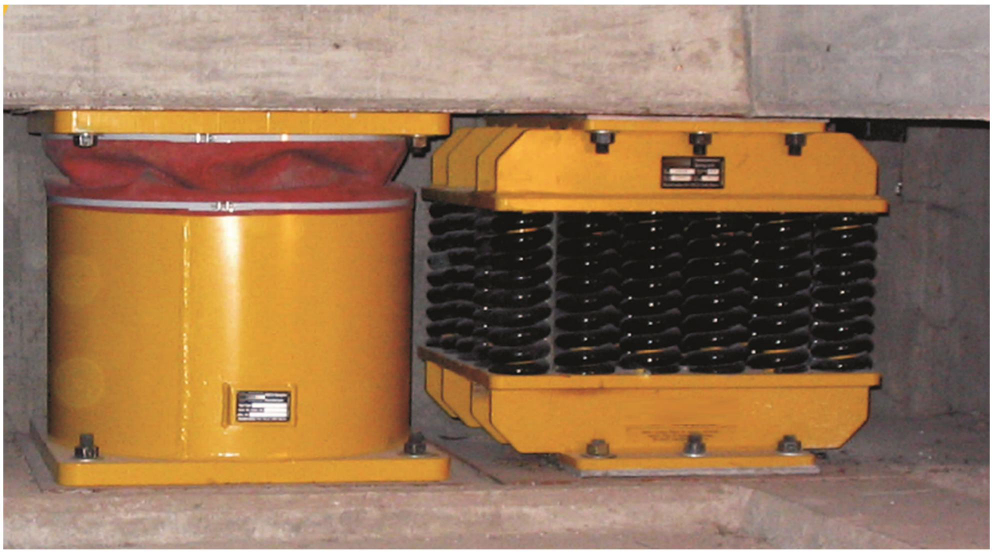

Figure 1. Viscous damper (left) and spring element (right) below concrete building

The use of the shown devices might have several advantages on the seismic performance of the structure when the BCS elements are chosen, arranged, designed, qualified and installed in an appropriate manner. Thus, it is recommended to contact the manufacturer of the devices as early as possible in the project process. This approach will help reducing numbers of iterative steps and will ensure the general feasibility of the chosen element parameters. The following steps are suggested for a successful performance of the BCS, the superstructure and the foundation / soil system below:

#1: Based on properties of the structure, the sub-structure and requirements of the desired performance of the BCS under the given seismic input, the vertical target frequency of the support system is chosen.

#2: The positions of the spring elements are selected at the level between the superstructure and the supports of the devices.

#3: The single springs should have the same or similar vertical displacements under permanent loads. A uniform vertical displacement is recommended to ensure the chosen vertical frequency. For a system which is almost rigid, the entire mass and centre of gravity plays an important role for the positioning of the elements. For flexible structures the support positions are regarded individually. Required vertical stiffness values can be calculated for each support location.

#4: The ratio between horizontal and vertical stiffness of the spring elements is chosen considering the seismic vertical and horizontal isolation requirements as well as the mechanical feasibility of the spring design.

#5: All the relevant frequencies and mode shapes of the entire system are calculated. For structures which are almost rigid six rigid body modes are existing. For flexible structures like, for instance, many buildings, the elasticity of the superstructure plays an important role on the resulting frequencies and mode shapes.

#6: Check of all target frequencies and mode shapes as well as of feasibility and capacity of suitable spring elements. If results are not favourable, repeat process from #1.

#7: Choice of horizontal and vertical damping resistance of single dampers. Selection of damper quantity & distribution below the superstructure in order to limit the BCS seismic relative displacements to a demand amplitude.

8: For rigid bodies 6 mode shapes & frequencies are existing as well as the corresponding damping ratios. For elastic structures, damping of the elastic modes might be considered ("composite modal damping") when determining the damping ratios for the governing mode shapes / frequencies.

#9: Check of structural seismic performance (acceleration, stress & strain levels, support reactions, displacements, …) by dynamic analysis for different seismic input levels (DBE, BDBE, CS, etc.). Use of linear modal analysis, linear time-domain investigations and/or non-linear time domain analysis, if necessary. Corresponding regulations must be checked. If performance targets are not achieved, start again at #7 or even at #1.

#10: Check of feasibility/capacity of damper elements. If not feasible, start from #7.

#11: Detailed design of corresponding hardware, i.e. spring elements and dampers. Analytical check of relative displacements and stress levels in these elements under the different seismic input levels.

#12: Pre-qualification of hardware (springs, spring elements, dampers) by static and dynamic testing according to current regulations, at least under DBE, BDBE conditions.

#13: Development of production quality assurance programs.

#14: Development of Installation, Inspection and Maintenance Manuals.

PORTA NUOVA BUILDING IN MILAN

A good project example for the previously described procedure is presented in this chapter. The Porta Nuova project in Milan, Italy includes several building complexes, a new metro station, parks and some underground parking. The building "D" is located in close proximity to the southern subway tunnel that passes under the site. The subway line may cause vibration and structure-borne noise problems within the building. By elastically supporting the building, these effects can be significantly minimized. For this purpose, a vertical system frequency of approximately 3.1 Hz was proposed by the consultant. Thus, the Step 1 of the layout process was finished. Due to the seismic risk at site it was already obvious that the spring elements should be combined with viscous dampers. Figure 2 shows a section of the arrangement of the elements below the building. Here, the elements are placed on a concrete base about 2.0 m high. This means that the space below the floor slab can also be used by the building's occupants.

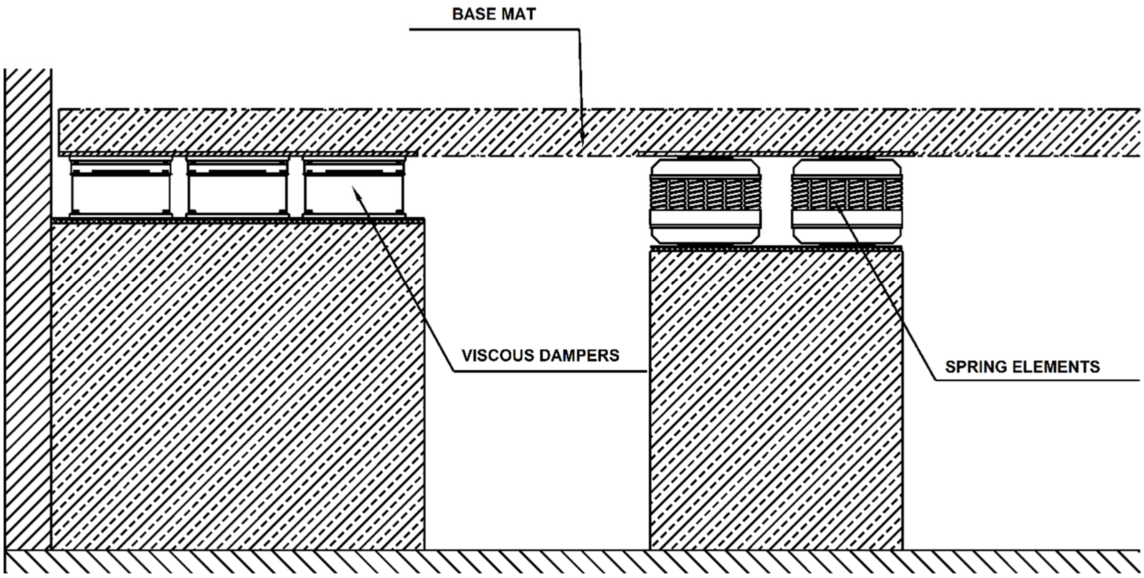

Figure 2. Devices below the floor slab of the building.

The building is approximately 22.0 m long, with a width of about 28.0 m and a height of 60.0 m. The total weight is estimated with 25500 metric tons. The seismic excitation can be described by the peak ground acceleration of approx. 0.07 g and a plateau range between 2.63 and 7.14 Hz with an amplification factor of 2.65. The selection of the element type and the arrangement of the elements were initially made considering the mentioned static building loads and the local space conditions. The elements vary in the bearing capacity, in the horizontal and vertical stiffness properties, in the ratio between horizontal and vertical stiffness and in the damping resistance values, as described in Siepe and Nawrotzki (2015). These features allow the adjustment of the element parameters in regard to the specific requirements of each projects. For several projects it is an advantage to use a higher stiffness ratio of the spring in a range of about 6 and 8. This parameter is used to control the seismic motion of the elastic supported system and could lead to a significant reduction of acceleration amplification.

After some preliminary calculations have been carried out it was decided to place the structure on 276 spring elements. The used type of spring exhibits a high stiffness ratio between vertical and horizontal stiffness of about 7. Thus, a low horizontal natural frequency and a corresponding mode shape with a low rocking component could be achieved. Parallel to the spring elements, 32 viscous dampers were arranged to increase the structural damping while limiting the relative motions of the building to the environment. A view of the building can be seen in Figure 3

Figure 3. View of building.

The elements can safely support the static loads and provide sufficient margin for additional movements occurring in all three spatial directions as a result of dynamic loads (e.g. due to earthquakes). Completion of the project, which began in 2009, was in 2014. Together with the experience of several other projects, like important machinery and a spent fuel storage tank, as presented in Nawrotzki and Siepe (2015), it appears possible to install a complete NPP building (e.g. Reactor building and/or even the complete Nuclear Island) on top of a spring-/damper system. More details are discussed in the next chapter.

NPP BUILDINGS

Entire buildings or some parts of buildings in nuclear power plants have to be protected against possible seismic events and other extraordinary load cases. So far, there are more than 100 buildings worldwide nowadays supported on helical steel spring elements. In most of these cases the elastic support is required to provide vibration isolation efficiency, e.g. if there is a train passing by closely. The high-frequency excitation in vertical direction, which may disturb or endanger the structure, is filtered out by the low vertical support frequency. At seismic sites this support strategy is modified and optimized to consider also the effects of earthquakes, as already described in this contribution.

The seismic efficiency of a Base Control System has been proven in real earthquakes. For instance, in 2005 it was feasible to measure the seismic response of a base-controlled apartment building in Argentina in comparison to an identical, adjacent building without protection measures. The effect of the BCS can be seen by comparing the measured results. The horizontal maximum accelerations at top of the building are reduced by more than 70 %. It is presented in Stuardi et al. (2008) that similar to the acceleration reduction also the corresponding structural responses like internal forces and subsoil reactions could be reduced significantly.

Thus, it seems absolutely possible to install the a complete NPP building on top of a Base Control System. To assess the reduction effect of such a system on an NPP structure such as the reactor building, numerical calculations of a structure, weighing approximately 150.000 metric tons were performed. It is shown in Nawrotzki et al. (2013) that the proposed control system leads to a significant reduction of the accelerations, base reactions and the values of the floor response spectra. An example for the comparison of in-structural response spectra is given in Figure 4.

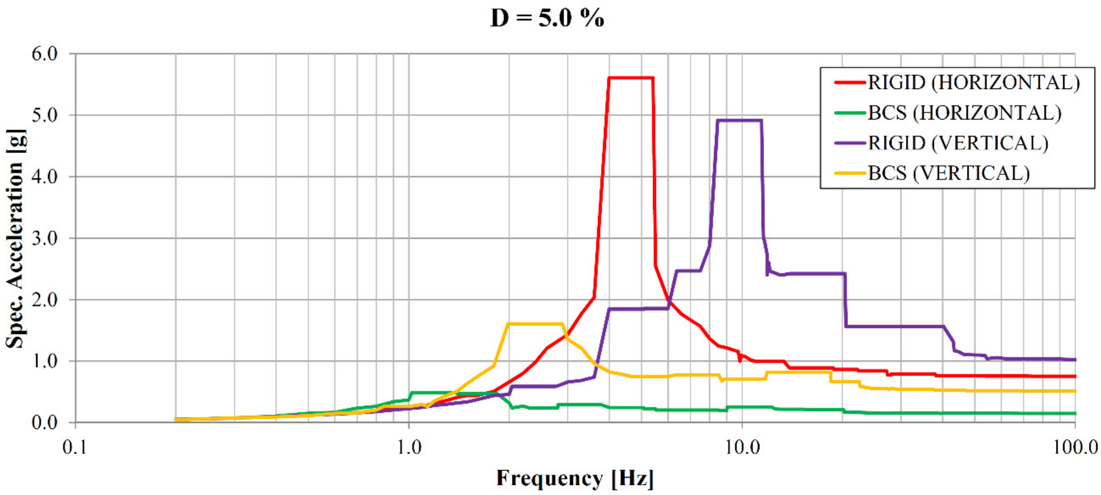

Figure 4. View of building.

The shown spectra are generated considering that the peak accelerations are assumed to be constant for a frequency range of ±15 % of the corresponding frequency (frequency widening). Having a look at these results it can be summarized that the application of a BCS leads to a significant reduction of the spectral values of the floor response spectra in a wide frequency range in horizontal and vertical directions. In comparison to other (e.g. horizontal protection systems) it should be noted that only small values of relative displacements between building and vicinity are expected. The corresponding connections, e.g. pipework systems, have to be designed to withstand such relative motion. Thus, it is important to optimize the parameters of the seismic protection system – to find an optimum between reduction of accelerations and occurring relative displacements. Having a look at executed projects (e.g. buildings, machine foundations, equipment) it was found that vertical support frequencies in a range of 1.0 to 3.0 Hz combined with horizontal frequencies within 0.5 and 2.0 Hz are typical layout criteria. The corresponding damping ratio amounts to about more than 10 % in vertical direction and to about more than 20 % in horizontal direction to reduce the seismic demands and to control the relative motions.

Beneath using the aforementioned general layout parameters, it is also possible to apply a more complex optimisation process, based on a “goal function”. Kostarev et al. (2017) proposed a goal function based on the peak accelerations at the support level and the maximum relative displacements at the isolator units. This criterion was applied successfully for the investigation of the parameter optimization for the seismic isolation of a PWR Reactor Building having approximately 80 meters in height. The results, presented in Kostarev et al. (2019), are presented it Table 1.

Table 1: Optimum layout criteria for a typical reactor building.

Characteristic		**Comment**
Vertical Frequency [Hz]	around 3.0	quite typical support frequency
Horizontal Frequency [Hz]	around 0.9	Very efficient reduction of seismic demands
Damping Ratio [%]	within a range from 20 to 40	reduction of seismic demands & control of relative motions

It could be concluded that these results are in very good consistence with the described values from other studies and projects.

CONCLUSION

After a short introduction into the layout process of a three-dimensional seismic control system, some corresponding examples for earthquake protection were discussed especially using Base Control Systems. Seismic demands like absolute accelerations, internal forces, support reactions and floor response spectra can be significantly reduced if these systems are applied. The use of a 3-dimensional Base Control System should be further investigated for practical application in NPP structures including planning ahead for future challenges, such as climate change. Stendel and Christensen (2002) mentioned that under warmer climatic conditions the permafrost terrain would be vulnerable to subsidence. Here, too, the pre-stressable spring devices can be used for adjustments and levelling, as for the already mentioned well-known soil settlements (e.g. due to mining subsidence or soft soil conditions).

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