MODULARITY OF 3D SEISMIC ISOLATION SYSTEMS

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ABSTRACT

The growing global interest in Small Modular Reactors (SMRs) stems from their inherent flexibility in power generation and their ability to adapt to various site conditions. However, ensuring seismic resilience is crucial, especially for standardized structural designs intended for varying seismic environments. This paper investigates advanced three-dimensional (3D) seismic isolation strategies utilizing helical steel spring elements and viscous dampers to enhance the seismic performance of nuclear structures. A 3D system consisting of independently adjustable stiffness and damping values allows precise tuning of structural response across all spatial directions. By optimizing stiffness ratios and damping values, the system effectively reduces seismic accelerations and mitigates resonance amplification. The modular approach enables site-specific adaptation by adjusting the number of dampers and spring elements, facilitating installation across different seismic zones. A simplified numerical analysis, using finite element modelling, assesses the performance of a SMR structure under varying seismic intensities. Results demonstrate that increasing the stiffness ratio significantly lowers horizontal frequencies while minimizing vertical displacements, leading to a substantial reduction in acceleration amplification. The study underlines the effectiveness of the proposed support system in achieving optimal seismic mitigation while supporting the modularity principles of SMR or other nuclear structures.

INTRODUCTION

The global interest in small and/or medium sized reactors has been on the rise in recent years. Two of the primary reasons for their popularity are their ability to provide flexible power generation. Many countries and large power consumers recognize them as a clear path to meeting carbon emission standards to mitigate climate change, as stated by IAEA (2022). The various SMR developments differ in numerous details. However, ground motion caused by earthquake may adversely affect these structures and critical components. The requirements are particularly high if a standard structural design is planned for locations of varying seismic demands, such as on both the east and west coast of the USA.

This contribution illustrates seismic control strategies using 3D systems. These systems enable the tuning of the rigid body modes of the supported structure into the low frequency range while providing large damping values in all three directions, as described in Nawrotzki et al. (2013). Historically, the focus has predominantly been on analysing systems for horizontal seismic protection, with horizontal earthquake inputs being the primary consideration. However, there is now a growing emphasis on the vertical direction, particularly in the qualification of support elements, such as those for SSCs (“Structures, Systems and Components”). Important issues such as uplift and vertical tensile forces must be investigated in detail.

One suitable system consists of helical steel spring elements and viscous dampers. The spring devices provide horizontal and vertical stiffness parameters while the dampers yield high damping forces in all three spatial directions. These devices are installed between the substructure and the superstructure, as shown in Fig. 1.

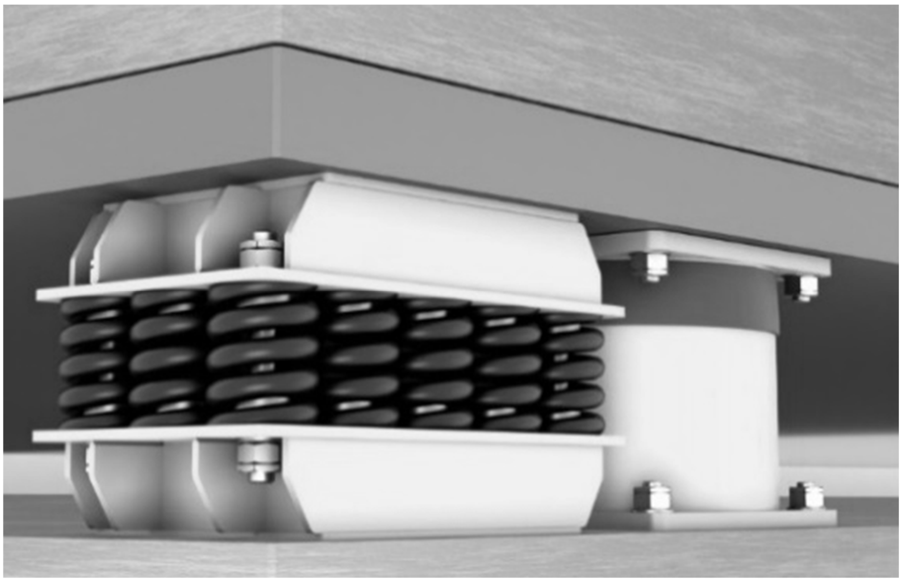

Figure 1. Spring element and viscous damper below a structure.

The different tasks of the seismic isolation system are clearly divided between the two discrete devices. The spring elements support the weight of the structure and provide flexibility. The viscous dampers provide damping forces to control resonance amplification, which is an important part of the mitigation strategy as explained in Siepe et al. (2023). If the modularity of a specific SMR project intends that the structures are to be installed at several sites with different seismic requirements, the aforementioned separation is very crucial. Based on the qualification of a single spring element and a single damper for the project, the design for the superstructure is repeated with more or less spring devices (higher or lower frequencies) and more or less dampers based on the seismicity of the chosen location of the plant and the residual safety margins of the devices. In addition to the described seismic performance improvement, effective vibration isolation and pre-stressable elements also offer additional advantages for installation and potential changes in requirements. The effects of soil settlement can easily be compensated, as presented in Siepe et al. (2024).

SEISMIC PROTECTION STRATEGIES USING 3D DEVICES

Since earthquakes not only induce horizontal ground motion but also significant vertical motion, it is becoming increasingly important to provide earthquake protection in all three spatial directions. The severe earthquake in Turkey in February 2023 demonstrated that very high accelerations can also occur in the vertical direction. Furthermore, 3D seismic isolation systems become important when, for example:

- the structure is located in a near fault zone and/or vertical effects are significant,
- uplift or tension forces for unprotected or 2D systems are expected,
- displacement demands of unprotected or 2D systems are too high,
- seismic soil pressure or stress distribution of unprotected or 2D systems are too high,
- unconditional use during and after the event becomes essential.

Seismic control can be achieved through the strategic arrangement of devices within structures to modify their response to seismic input. This modification can be accomplished by the increase of structural damping, the modification of the fundamental mode shape and/or the increase of the fundamental period. The first approach involves the installation of discrete dampers to enhance structural damping. The anticipated reduction in induced structural responses is supported by various national and international standards. According to ASCE 7-22 (2022), an increase in structural damping from 5% to 20% results in a correction factor of 0.67. Consequently, a reduction in structural stress, strain, and displacement in the range of 30% to 40% is expected.

The second and third mitigation strategies are often realized by placing the structure on an elastic support system. Flexible structures typically exhibit a lower risk of collapse during seismic events. Low natural frequencies indicate a reduced level of induced seismic energy, while structures with higher natural frequencies tend to absorb more energy from base excitation. This strategy is further justified when analysing the seismic design response spectrum. The subsoil properties should be at least of "medium" quality, ensuring that the frequency range of maximum amplification in the response spectrum is sufficiently high. Otherwise, resonance effects may occur even in passively controlled structures, or the target frequency may be too low to maintain the proper serviceability of the structure without additional precautions. If the corner frequency amounts to be at 3.0 Hz a reduction to a frequency of about 1.0 Hz will reduce the seismic demands by 1.0/3.0 = 0.33, meaning a significant reduction of nearly 70 %. In an optimum case this frequency reduction is combined with the aforementioned increase of damping. The result can be taken from Fig. 2. Reducing the frequencies even further might be helpful to reduce seismic acceleration but at the same time the relative displacements will be increased. Thus, it is always an optimization process to align the resulting solution characteristics with the specific project requirements.

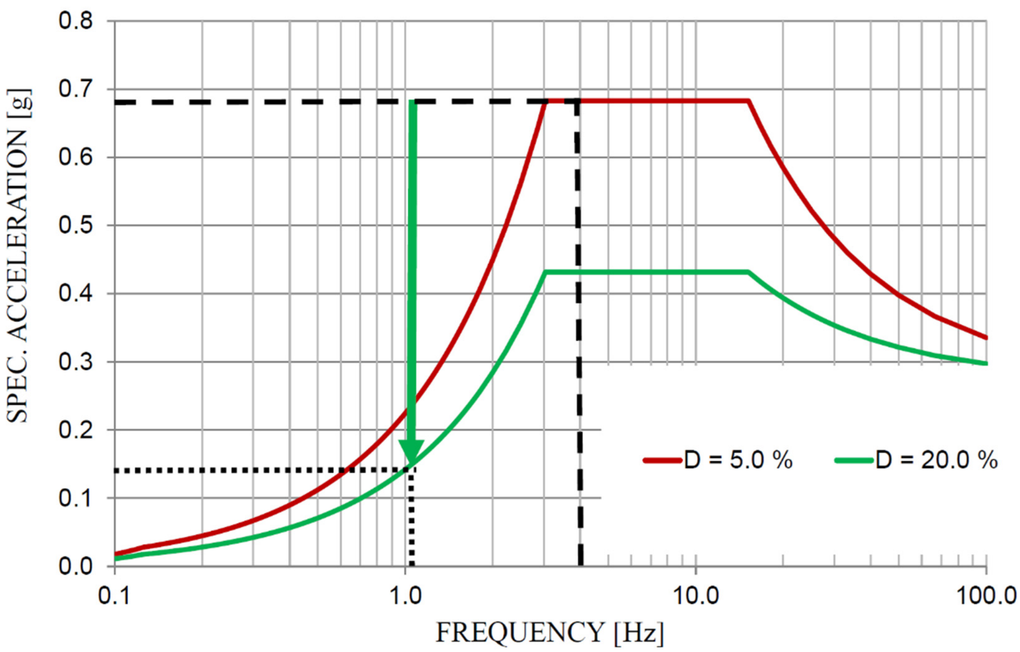

Figure 2. Elastic design spectra and efficiency of seismic protection strategy.

Nuclear installations are always based on a systematic description and investigation of risk, its mitigation and safety margins. Regular design spectra for 3 directions are used to describe the potential risk at a specific location (design basis, e.g. similar to the spectrum given in Fig. 2). Margins have to be added for the qualification of corresponding devices where it must be shown by test that the devices withstand these tasks without major deficits. One of the main requirements is that the devices must always be in the position to support the entire structure and possess specific restoring energy. Beyond design investigations and consequences of different failure routes belong to regular investigations in the scope of such installations.

A Base Control System (BCS) is a corresponding example for a 3D solution and consists of devices equipped with helical steel springs and viscous dampers, strategically positioned beneath the structure's base to support its weight. These devices are engineered with sufficient safety margin to accommodate additional loads in both horizontal and vertical directions, thereby providing flexibility in all spatial direction. The horizontal stiffness is uniform across both horizontal directions. The linear behaviour of the springs facilitates a straightforward numerical description, allowing for an effective assessment of the structure's performance when supported by these devices. The configuration of the flexible springs alters the fundamental mode shape of the supported structure and reduces the system's predominant frequency. In addition to the spring elements, highly efficient viscous dampers are incorporated, which generate absorption forces in all three spatial directions. The properties of these dampers can be characterized by their damping resistance values across the same three axes. These dampers play a vital role in absorbing kinetic energy, thereby increasing structural damping and serving as a limitation on displacements for both the structure and the devices.

When selecting the requisite properties of the BCS, it is essential to recognize that the devices exhibit variability in parameters such as bearing capacity, horizontal and vertical stiffness, the ratio of vertical to horizontal stiffness, and damping resistance values. These parameters can be tailored to meet project-specific requirements. In many cases, employing a higher stiffness ratio for the springs is advantageous, as it aids in controlling the seismic motion of the elastically supported system and can lead to a substantial reduction in acceleration amplification, as discussed in Siepe et al. (2023).

Near-fault earthquakes also emphasise the aspect of pulse-like seismic ground motion in horizontal and vertical directions. When such events are likely or occur it is important to underline that the fundamental response of the structure is modified through its support conditions which is always reacting passively and without delay. The response frequency is modified and damping forces are activated by seismic relative movements in the flexible support. When short time events with high acceleration levels occur, the main response intensity is lowered as the duration of the (first) cycle becomes larger than in case of the rigid connection. This characterization in 3 spatial directions is also important, e.g., when airplane crash situations have to be evaluated. Systems similar to the described BCS are regularly applied for installations with high impulse demands for many decades.

MODULAR CONCEPT

Modularisation is one essential part of the SMR power plant strategy. In general, it serves as a cost reducing mechanism by subdividing the plant into smaller units, or modules. These modules can be manufactured offsite in a controlled environment, potentially providing cost savings that compensate for their seemingly higher capital costs. The modularity is anticipated to reduce labour costs, as the workforce does not need to be relocated for the production of each power plant module. Additionally, cost savings are expected due to shorter project timelines associated with serial fabrication techniques and more efficient use of materials.

The modular principle can also be applied to earthquake protection by developing and designing a plant that can be constructed at different sites with different seismic requirements. This strategy provides additional challenges to the seismic isolation devices. If the chosen devices have elastic and damping characteristic (e.g. like for a HDRB – high damping rubber bearing) it will be very difficult to adjust the seismic protection solution according to different seismic input levels. In this regard, the previously described 3D Base Control System can offer advantages. As shown in Fig. 3, the system often consists of separate spring and damper elements.

Figure 3. Spring elements and viscous dampers below a 1600 tons reinforced concrete structure.

The spring devices have the task to support the weight of the structure and to provide flexibility in horizontal and vertical directions. The viscous dampers yield an increase of structural damping. Thus, for projects in low seismic zones it is possible to simply reduce the numbers of dampers. More dampers can then be arranged at high seismic sites. The clear distribution between devices that ensures flexibility and other devices that yield damping forces support the modular concept strategy. The qualification of the elements can also be adapted to the requirements of the modular concept. In the case of dampers, it is recommended to always use the same type and, as described above, to make the adjustments solely via the number of elements. In the case of spring elements, only the particular spring is usually qualified. This makes it possible to use elements with varying quantity of these springs. In this way, the required qualification effort can be reduced. If another spring (e.g. with a different ratio of vertical to horizontal stiffness) is qualified, it would also be possible to adapt the spring element type to the site-specific seismic conditions. In principle, it is also possible to maintain the vertical support frequency if necessary. In general, also the mass of the supported structure can be regarded as one part of the modularity, because only the dynamic properties/behaviour (in terms of frequencies, modes shapes and damping ratio) are relevant. The main components of the modular concept are summarized in Table 1.

Table 1: Modularity.

Mass	More or less mass		
Spring devices	More or less spring devices	More or less springs within the same type of element	Different type of spring
Damping	More or less damper devices		

CALCULATION EXAMPLE

Numerical calculations of a structure, weighting 15,000 metric tons were performed to assess the reduction effect of a 3-D Base Control System on a typical SMR structure such as the reactor building. Beneath the evaluation of the improved seismic behaviour of the structure itself, the purpose of the feasibility study is to investigate the effects of seismic control on the resulting relative displacements of the devices. The structure is represented with one single mass joint with inertia moments around the three main axes, based on a simplified cube. The longitudinal axis is the x-axis. The y-axis is the transversal axis and the z-axis represents the vertical direction. For the study three different finite element models of a rigid-body structure (length = 20 m, width = 15 m and height = 10 m) are prepared using the commercial software SAP2000 from CSI (2025). The mentioned three different models are used to investigate the effect of different parameters of the support system.

The starting point for the comparative study is the selection of a typical vertical support frequency of 3 Hz with an associated damping ratio of 5%. As described in a previous chapter, the behaviour of the structure can be influenced by selecting the stiffness ratio of the spring. Therefore, a stiffness ratio (vertical to horizontal) of 1.0 (option 1), 3.0 (option 2) and 7.0 (options 3 & 4) is considered within the 4 variants. Furthermore, the damping is also significantly increased in option 4, because this option represents the optimum solution. A more detailed procedure for the layout of a 3D seismic protection system is described in Nawrotzki et al. (2024). A 3-dimensional elastically supported rigid body yields a total of 6 modal eigenmodes, as described in Nawrotzki et al. (2017). Table 2 compares the corresponding modes and data of the 3 investigated options.

Table 2: Rigid body modes and corresponding frequencies and damping ratio.

	Option 1	Option 2	Option 3	Option 4
Rocking mode in x-direction	2.18 Hz, 6 %	1.57 Hz, 5 %	1.09 Hz, 5 %	1.09 Hz, 25 %
Pendulum mode in x-direction	4.51 Hz, 10 %	3.62 Hz, 11 %	3.41 Hz, 11 %	3.41 Hz, 27 %
Rocking mode in y-direction	1.98 Hz, 5 %	1.49 Hz, 5 %	1.07 Hz, 5 %	1.07 Hz, 24 %
Pendulum mode in y-direction	4.87 Hz, 10 %	3.72 Hz, 11 %	3.42 Hz, 10 %	3.42 Hz, 27 %
Translation in vertical direction	3.00 Hz, 5 %	3.00 Hz, 5 %	3.00 Hz, 5 %	3.00 Hz, 11 %
Rotation around vertical axis	3.74 Hz, 12 %	2.16 Hz, 13 %	1.41 Hz, 12 %	1.41 Hz, 60 %

When looking at the previous table, it is clear that a higher stiffness ratio initially reduces the decisive horizontal frequencies. However, it is not the frequency alone that plays an important role in the dynamic behaviour of the structure, but also the corresponding mode shape in particular. As the stiffness ratio increases, the rocking part of the horizontal mode shapes is reduced. More detailed information on this can be found in a later section in the results under earthquake excitations. The seismic input is based on the horizontal spectrum defined in U. S. Nuclear Regulatory Commission (2014). Increasing intensities of the peak ground accelerations (0.05, 0.1 and 0.3 g) are used for the study. The following Fig. 4 presents the corresponding spectrum, scaled to 0.3 g as an example. Furthermore, one artificial time history data set is shown in the same figure.

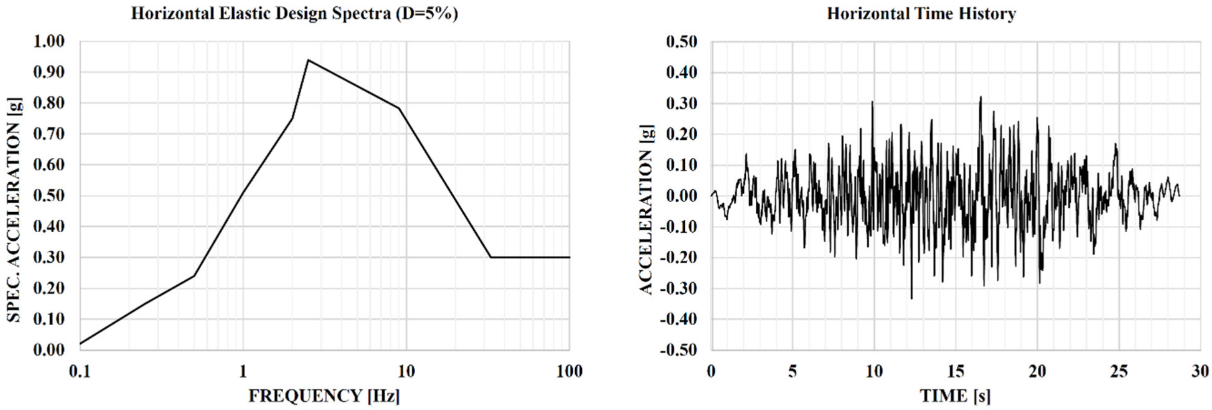

Figure 4. Seismic input, spectrum (left side) and corresponding artificial time history (right side).

Modal time history analyses were performed using the shown time history as base excitation at the restrained nodes below the structure support devices. The linear calculations considered just an excitation in longitudinal direction to simplify the study and to provide a clearer overview of the results. The main results are summarized in Table 3.

Table 3: Comparison of seismic results.

	Option 1	Option 2	Option 3	Option 4
PGA = 0.05 g				
Horizontal absolute acceleration at centre of gravity [g]	0.11	0.10	0.09	0.05
Horizontal relative displacement at corner device [mm]	3.0	8.5	16.7	8.3
Vertical relative displacement at corner device [mm]	4.2	3.6	3.0	1.6
PGA = 0.10 g				
Horizontal absolute acceleration at centre of gravity [g]	0.22	0.21	0.17	0.10
Horizontal relative displacement at corner device [mm]	5.9	17.0	33.4	16.6
Vertical relative displacement at corner device [mm]	8.4	7.3	6.0	3.3
PGA = 0.30 g				
Horizontal absolute acceleration at centre of gravity [g]	0.65	0.62	0.52	0.29
Horizontal relative displacement at corner device [mm]	17.8	51.1	100.3	49.7
Vertical relative displacement at corner device [mm]	25.1	21.8	18.1	9.9

It should be noted that the first three option might be not applicable for the highest seismic input (as shown for PGA=0.30g), as the resulting accelerations are quite high and some relative displacements are close to uplift situation. Due to the choice of an equal vertical frequency of 3.0 Hz for all options it has to be noted that there is a corresponding vertical static deflection of about 28 mm within the spring devices. Thus, for the highest seismic input (0.3 g) option 4 is the optimum solution. When looking at the results summarised in the table for stiffness ratio 1.0 (option 1), 3.0 (option 2) and 7.0 (options 3 & 4), it appears that the choice of a higher stiffness ratio significantly reduces the vertical relative displacements in the elements. This is due to the reduced tilting component of the decisive first horizontal mode shape. In addition, the positive effect of the lower horizontal frequency and increased damping in option 4 can be seen in the significant reduction in the accelerations. It can be concluded that an optimised solution can be found by changing the support parameters. Overall, option 4 appears to be optimal. In accordance with the modular concept, the number of dampers for the lower earthquake excitation scenarios could also be reduced in this option, if there are no project-specific reasons to the contrary.

A typical project example that uses a spring device with a stiffness ratio of about 7.0 is the elastic support of an equipment in a NPP. Fig. 5 shows a picture of these devices.

Figure 5. 3D elastic support system below a spent fuel storage tank.

Equipment in (nuclear) power plants can be supported by helical steel springs and viscous dampers to mitigate excitation due to seismic events and/or shock loads (e.g., from aircraft impact). The safety of these structures is of particular interest as they often consist of sensitive materials. The mentioned example is the spent fuel pool in a nuclear power plant located in a high seismic zone in Switzerland. The pool dimensions are approximately 20.0 x 10.0 meters with a height of about 14.0 meters. The total operating mass of this structure is approximately 5800 metric tons. A peak acceleration value of nearly 0.5 g just below the elastic support system must be considered. A seismic protection system had to be developed to reduce potentially very high response accelerations. The target values were set such that the waves generated from a seismic event on the water surface should not overflow the top of the pool walls, and the integrated steel racks should not contact each other.

The devices are arranged between the pool and the surrounding building. They were specifically designed for the application to achieve relatively low structural frequencies of the spring-supported system. Simultaneously, the damping of the corresponding mode shapes is increased. Combining these measures reduces acceleration and prevents water overflow. In this particular case, a modular concept was not required. It was decided to apply spring elements and combination spring-damper devices, instead of separate damper devices. The system was successfully installed in 2008. As the elements were pre-stressed, they served as rigid support during the construction of the pool itself. An additional advantage of this type of support system is that these elements also allow for easy adjustment of the system in case of later differential settlement or if any other modifications would be necessary during the lifetime of the installation. Access to the devices is an important design element, ensuring that a visual check of the elements is always possible.

CONCLUSION

3D seismic isolation systems are an effective means to control structural and nuclear component response to vertical and horizontal ground shaking. However, the need for high degrees of structural damping, for example, can be independently modified to adjust to site specific demands. Therefore, the numbers of applied dampers can be modified. Using the same type of spring devices and/or using different numbers of the same spring in different devices allow for further modularization. The important qualification processes are simplified, because only one type of damper and one type of spring need to be investigated. The use of the presented systems should be further investigated for practical application in SMR projects especially with regard to the modular concept and required qualification processes for the seismic mitigation devices.

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