Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

# MOTIVATION FOR 3D SEISMIC ISOLATION SYSTEMS

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## ABSTRACT

Recent developments in seismic engineering have highlighted the need for three-dimensional (3D) seismic isolation systems to address both horizontal and vertical ground motions effectively. While some seismic protection strategies primarily focus on horizontal isolation, emerging research and revisions in seismic standards (e.g., chaper 11.9 of ASCE 2022) underscore the significance of incorporating vertical motion considerations, particularly for structures located near fault zones. This contribution critically evaluates the advantages of 3D seismic isolation systems over conventional two-dimensional (2D) approaches, emphasizing key factors such as uplift prevention, soil reaction control, and mitigation of higher-mode effects besides the reduction of vertical response acceleration. The reduction of the horizontal frequency is not the sole criterion for designing or evaluating a support system. In a 3D overall situation, the general issue is much more complex. The incorporation of helical steel spring devices, coupled with 3D viscous dampers, enhances vertical flexibility, minimizes relative displacements, and ensures improved energy dissipation. This paper underscores the necessity of integrating 3D seismic isolation into modern structural design to enhance resilience, reduce structural vulnerabilities, and ensure long-term stability under multi-directional seismic loads.

## INTRODUCTION

The majority of research and developments of seismic protection focuses on horizontal effects of earthquakes and hence, the horizontal isolation by isolators. However, recent trends show that there is an increasing interest in 3D-solutions, as presented in Nawrotzki et al. (2021). Structures will always experience horizontal and vertical seismic excitations, that must not be neglected. In general, the 3D seismic isolation systems become important when the structure is located in, or close to a near fault zone and/or if vertical effects are significant. This contribution illustrates further reasons for the application of 3D systems. In particular, the characteristics of 2D systems with regard to uplift, soil reactions, relative displacements and interaction between horizontal and vertical action (“higher mode effects”) are motivating factors for evaluating 3D support systems.

Latest revisions of seismic standards (e.g. ASCE 2022) also provides more details about the vertical direction. Not only the last severe earthquake in Turkey in February 2023 showed that very high accelerations also occurred in the vertical direction, but there are important evaluations of seismically isolated buildings during the Tohoku 2011 Great East Japan Earthquake. Table 1, based on Saito (2015), presents the data of the three measured component motion of 8 different buildings with seismic isolation systems of different types. Saito (2015) concluded that the isolation systems showed a sufficient effectiveness in reducing horizontal accelerations and horizontal seismic loads on structural component. However, Table 1 also shows that the vertical component of the (real) seismic ground motion was increased by a factor of 2.0 to 2.5 on the upper isolated elevations of the buildings. Thus, the combined effect of reduced horizontal and amplified vertical responses compromises the overall effectiveness of the installed seismic isolation systems.

Table 1: Records of buildings with seismic isolation (SI) system (HRB: high damping rubber bearing, NRB: natural rubber bearing, LRB: lead rubber bearing, OD: oil damper, SD: steel damper

| **Site / Usage** | **Type of System** | **Location of sensors** | **Accelerations [g] (horizontal x / horizontal y / vertical z)** |
|---|---|---|---|
| Sendai / Office | HRB | under SI<br>above SI<br>top floor | 0.29 / 0.26 / 0.24<br>0.12 / 0.15 / 0.38<br>0.14 / 0.17 / 0.53 |
| Fukushima / Office | NRB, LRB, OD | under SI<br>above SI<br>top floor | 0.59 / 0.77 / 0.45<br>0.18 / 0.22 / 0.53<br>0.16 / 0.19 / 0.63 |
| Fukushima / Office | unknown | under SI<br>above SI<br>top floor | 0.42 / 0.34 / 0.33<br>0.19 / 0.23 / 0.47<br>0.16 / 0.16 / 0.59 |
| Tsukuba / Office | NRB, LRB, SD | under SI<br>above SI<br>top floor | 0.33 / 0.24 / 0.12<br>0.09 / 0.08 / 0.2<br>0.13 / 0.09 / 0.25 |
| Tokyo / Museum | HRB | under SI<br>above SI<br>top floor | 0.102 / 0.08 / 0.09<br>0.08 / 0.09 / 0.09<br>0.1 / 0.08 / 0.09 |
| Tokyo / Office | NRB, LRB | under SI<br>above SI<br>top floor | 0.11 / 0.09 / 0.06<br>0.06 / 0.04 / 0.06<br>0.1 / 0.08 / 0.11 |
| Kawasaki / Residence | NRB, LRB | under SI<br>above SI<br>top floor | 0.09 / 0.11 / 0.03<br>0.06 / 0.07 / 0.05<br>0.06 / 0.07 / 0.06 |
| Odawara / Office | NRB, LRB | under SI<br>above SI<br>top floor | 0.14 / 0.12 / 0.05<br>0.06 / 0.14 / 0.05<br>0.06 / 0.07 / 0.05 |

Before considering the specific advantages of 3-D systems, it is helpful to examine the degrees of freedom of an elastically supported system, as shown in Nawrotzki et al. (2017). Assuming a rigid body structure, the system possesses six degrees of freedom, as it can translate in the three directions x,y and z and can rotate about the x, y and z axes. This principle is shown on the left side in Fig. 1. Having a look at the structure shown on the right part of Fig. 1 it is obvious that a real structure is more complex than this simplified rigid body model. In addition to the 3-dimensional earthquake input, the 3-dimensionality of the real structure also plays a decisive role in its behaviour. While the vertical earthquake input is often neglected for the pure load transfer, with the justification that the design dead weight already includes safety factors, this is absolutely not permissible for more precise analyses (e.g. in-structural response spectra). Here, the local mode shapes and elasticities of the structural members must also be taken into account. Other components (e.g. machinery, equipment) must also be modelled in 3-dimensions.

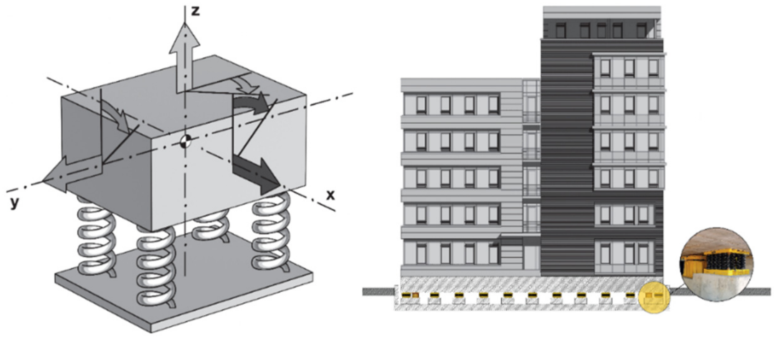


Figure 1. 6 DOF of a "rigid" structure (left ) and building supported on a 3D support system (right ).

Observing this figure and considering the support system provides horizontal and vertical flexibility, it becomes evident that purely horizontal eigenmodes are not feasible. Besides the vertical stiffness, which determines the vertical frequency and ensures vertical vibration isolation efficiency, the stiffness ratio between vertical and horizontal stiffness plays a governing role, as described in Nawrotzki et al. (2015). A higher stiffness ratio yields mode shapes with lower horizontal frequencies and lower levels of induced rocking motion.

If helical steel spring devices are chosen as part of a 3D seismic protection system, additional advantages are achieved. They provide an easy mechanisim for height adjustment, accommodating settlement issues and the exchange of devices. Moreover, they allow for careful control of vertical (permanent) forces. Vibration isolation and protection against structure borne noise is already inherent in the basic design of these elements. In combination with 3D viscous dampers the seismic demands of the structure and effects of extraordinary load cases such as impact due to airplane crash are reduced significantly.

## WHY 3D SEISMIC ISOLATION SYSTEMS?

More than 20 years ago Chouw (2002) pointed out that simultaneous horizontal and vertical ground motions should be taken into account – at least in regions with expected strong vertical ground excitation. Under the seismic input details there are several other factors that underline the importance of 3D seismic isolation systems. This section provides a concise overview of the primary reasons to investigate 3D systems.

### *Vertical Effects*

As previously mentioned, the vertical seismic input should be taken into account. While some design codes disregard or neglect vertical ground motions, there appears to be a general trend towards incorporating vertical design spectra. For instance, ASCE (2022) includes specific details for a vertical design spectrum instead of merely providing a multiplication factor for the horizontal input. In the nuclear industry, the distinction between horizontal and vertical seismic design spectra is considered "state of the art," supported by standards or guidelines such as Reg.Guide 1.60, as outlined by the U.S. Nuclear Regulatory Commission (2014). The vertical input becomes particularly pertinent in near-fault sites, and it warrants further investigation to determine whether a 3D seismic protection system should be employed instead of a "fixed-base" or conventional 2D isolation system.

In general, there is no exclusive vertical seismic action or response as the excitation is always 3D with more or less weighting of horizontal and vertical components. Thus, it is quite difficult to investigate the reasons for damages occurred during a seismic event. Nayak (2021) showed several examples where their damage was caused predominant with vertical ground motion – e.g. during the 1994 Northridge and/or the 1999 Izmit earthquakes. Especially horizontal structures (ceilings, floors, balconies, horizontal heat exchangers, pumps, etc.) are sensitive to vertical motion and effects like overturning of equipment are always a combination of horizontal and vertical action. Table 1 shows that significant amplification of vertical responses along the height of a structure are possible in different constellations even under quite small seismic input. For sensitive structures or sensitive use of buildings it has to be shown by analysis or test that there is no unexpected behavior of any equipment, component or structure under 3D excitation and the corresponding structural spatial responses. Corresponding design guides especially for nuclear structures and equipment are complex and more strict than for regular buildings.

***Uplift***

If there is very high vertical excitation or the horizontal earthquake input is very large and/or the structure is very slender, uplift problems may occur especially at the corner locations. An unprotected structure might be in danger and could be protected by special piling that take tension forces. Typical 2D isolation systems (e.g. high damping rubber bearings, friction pendulum systems etc.) are very flexible in horizontal direction but have a very high vertical stiffness. In other terms, their vertical deflection (for rubber bearings) and/or general sensitivity to vertical motion (e.g. friction pendulum systems) would be a problem for the aforementioned seismic input scenario. The devices are usually not designed for tension, even if some of them might be suitable for vertical uplift forces. Thus, a system should be chosen, that could take tension forces or is able to avoid tension/uplift at all, depending on the site-specific data. For extreme conditions where complete decoupling of translation and vertical displacement is required, combining devices of different seismic protection systems is feasible. Nielsen et al. (2021) presents an innovative 3-D seismic isolation system that combines a lateral isolation systems of triple pendulum isolators, large 1-D fluid dampers and a vertical protection systems consisting of steel pedestals, helical steel springs, viscous dampers and low friction sliding shear pins.

***Soil Reactions***

The soil pressure could be understood as a global indicator for the stability of the structure as the foundations serve as a reliable basis for the proper operation of all structural members. Depending on the site-specific conditions the peak responses of unprotected structures may exceed allowable values and often risking uplift at the foundation corners. Also, for 2D seismic protection systems the seismic soil reactions or stress/strain distribution is too high. Furthermore, often the devices are not suitable for uplift or vertical tension forces. The three-dimensional spring devices offer a certain vertical flexibility that acts as a buffer, significantly reducing the internal strains of the supported structure and the loading on the substructure or soil. If necessary, specialized springs can also bear and transfer vertical tension forces. Ghiocel (2019) demonstrated, by using highly sophisticated three-dimensional SSI and finite element simulations, that 3D springs and dampers are more effective than 2D lead rubber bearing isolators, particularly for vertical motion. For more detailed information on the positive effects of 3D versus 2D protection systems on in-structural response spectra, refer to Ghiocel (2019).

***Soil Settlement***

Building subsidence and differential soil settlements are common occurrences worldwide. The underlying reasons and anticipated displacements can differ significantly from one case to another. For instance, former or existing mining and excavation activity from tunnel drilling for traffic line expansion pose significant risks to structures. Climate change also contributes to settlement problems. Structures supported on extremely stiff devices would face substantial change to reaction forces or other issues if settlement occurs. Therefore, if soil settlement is anticipated, seismic protection strategies should also consider this aspect.

Prestressable spring elements as found in some 3D base isolation systems offer potential abatement. As settlement occurs the elastic spring expands to compensate for settlement, while still providing reaction loads to the supported structure. The prestressability allows height adjustment by adding/subtracting steel shims. Even, if further settlement occurs more shims can be added to maintain the desired elevation. In these cases, the relatively low vertical stiffness of the springs results in small corresponding changes in spring forces. Thus, the action of shimming is applied to maintain the height without increasing loads or load redistribution. As an example, the 600 year old St. Remigius Church in Bergheim, Germany, shown in Fig. 2. suffered some damage (cracks) during the last decades due mining activities. The responsible geological fault line affected the eastern part of the church. Spring elements were retrofitted between two separated foundation systems as a remedy against vertical displacement.

Figure 2. Church in Germany (left side), Situation during retrofitting works (right side).

***Relative Displacements***

In general, the extended relative seismic displacements of internal and external structures require additional flexibility of distribution systems (umbilical problem). Reducing frequencies (respectively elongation of period) would typically reduce seismic acceleration but will increase relative displacements. As most of the common 2D seismic protection systems yield a very low frequency they have to accommodate large horizontal motion. The devices (e.g. a triple pendulum friction system) are optimized for these large displacements that could typically reach more than 0.5- 1.0m. For the supported structure this motion may not provide any special challenges but for the surrounding structures and/or any structure (e.g. piping systems) that leaves the supported building these large relative displacements could pose a severe danger. A 3D system using springs and damper offers a combination of a relatively low frequency and high amount of structural damping which yields much smaller relative displacements. Table 2 provides typical values for the corresponding design values. More details are given in a project example in a following chapter.

Table 2: Design criteria for 3D seismic protection system.

| **Characteristic** | **Value** | **Note** |
|---|---|---|
| Vertical Frequency [Hz] | 1.0 – 3.0 | Typical support frequency |
| Horizontal Frequency [Hz] | 0.5 – 2.0 | Very efficient reduction of seismic demands |
| Damping Ratio [%] | >10 / 20 | Vertical / horizontal – reduction of seismic demands & control of relative displacements |

***Serviceability Limit State***

If the unconditional use during and after the event becomes essential it is important to reduce damage not only of structural members but also of non-structural members. Furthermore, keeping relative seismic displacements in a certain range will also help to ensure the usage of a structure. 2D seismic protection systems will help significantly to improve seismic behaviour especially in terms of reduction of accelerations, stresses and internal displacements. 3D systems, as already discussed, provide an additional advantage due to quite small relative displacements in the devices. Thus, any distribution systems that have to cross the seismic gap will benefit significantly from these smaller displacements.

***Exchange of Devices***

Due to the weight and size of the devices, a replacement has to be suitably prepared in terms of space, moving, and manpower. In general, the replacement of helical steel spring elements and viscous dampers is quite simple when compared to other seismic protection systems. Furthermore, the replacement could be done without damaging the sub- or superstructures. Due to the prestressability feature of the spring devices it is very easy to remove/exchange them, if required. The spring element can be prestressed by means of hydraulic jacks to achieve an air gap between the device and the superstructure, as presented in Fig. 3.

Figure 3. Spring device with hydraulic jacks and shimming action.

The prestressing bolts at the spring device corners can lockdown the unit to it's prestressed height. After all adjustment shims have been taken out, the spring unit can be removed. Depending on the specific situation, it might become necessary to temporarily prop the superstructure prior to starting this activity. As an exchange of these devices is very unlikely it might be more important to underline the advantage of control of vertical (permanent) forces – by adding or removing steel shims at the devices a certain adjustment is possible. The permanent vertical deflection of the springs typically range 2 to 4 cm. The corresponding vertical force can easily be calculated due the linear-load-deflection characteristics.

***Vibration Isolation***

The elastic support of rotating equipment or machinery using helical steel spring devices in conventional or nuclear power plant has already become standard practice worldwide as a means for efficient vibration isolation. For buildings or part of buildings within power plants this approach has been somewhat overlooked, but is expected to gain acceptance. 2D seismic protection systems focus on the modification of horizontal frequencies. Due to the stiff vertical support, there will be nearly no vibration isolation effect. The situation is different with 3D systems that utilise vertically flexible elements. Here, the vibration isolation efficiency is directly included in the system. This advantage is already used for main control rooms in several nuclear power plants. The steel springs and viscous dampers installed below the main control rooms satisfy a wide range of requirements (ensuring vibration isolation efficiency, seismic protection, protection against structure-borne noise and protection against shock load due to aircraft impact cases).

***Shock Loading***

Usually, the seismic load case is not the only governing case for the design of a structure. For nuclear power plants for example an airplane crash is an important emergency load case to consider. This input excites all three directions – thus a vertical stiff protection system might not be the optimum choice. Several structures or equipment inside the building should be protected against this load case especially as instructure vibration may be amplified where sensitive equipment may be installed. The detailed experience with the elastic supports of forging hammers bore the idea, that spring elements and viscous dampers could also protect a structure against shock input due to airplane crash. In both cases the helical steel transforms the high frequency impact into a low frequency response, while the dampers effectively bring the hammer/isolated stucture to rest before the next blow. Due to the low frequencies of the spring supported structure the high frequency content of the impact is filtered out.

***Qualification***

The qualification processes of seismic control systems is paramount in nuclear facilities.. Spring elements and viscous dampers as part of a 3D system have been supplied for various kinds of structures (large steam turbine foundations, spent fuel storage tanks, emergency diesel generators, main control rooms and equipment of all kinds) for more than 40 years in nuclear power plants and nuclear facilities. This general approach is becoming more sophisticated with an ever-increasing project demands, but also in particular with regard to quality assurance requirements. This further comes into focus as beyond design investigations and combined horizontal and vertical action are extending a typical qualification procedure, as presented in Fig. 4.

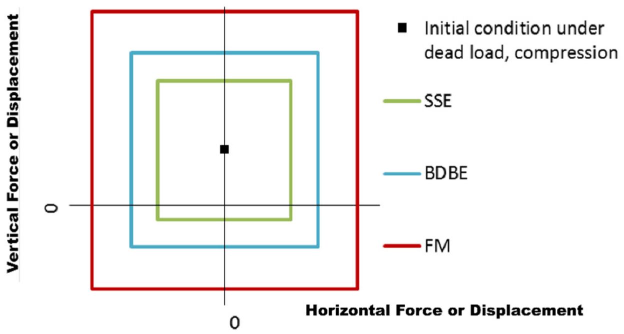


Figure 4. Overview 3D investigations (SSE: safe shutdown earthquake, BDBE: beyond design basis earthquake, FM: failure mode).

The previous plot summarizes the developed and executed procedure for nuclear applications. The black rectangle dot shows the permanent vertical static displacement of the spring elements. The corresponding qualification measures (e.g. testing of the devices) are developed for the mentioned 3D systems but must be considered also for other (e.g. 2D systems) as the seismic input and the corresponding requirements are always in 3D.

***Higher Mode Effects***

The oversight of vertical input components, neglect of vertical stiffness (particularly in 2D protection systems), and the coupling between vertical and horizontal behavior can lead to an inaccurate assessment of structural demands and the effectiveness of 2D systems. Regrettably, there are limited contributions exploring these effects. However, significant conclusions can be drawn from the NEES/E-

Defense collaborative program on base-isolated buildings, as discussed in Ryan et al. (2012) and Sasaki et al. (2012). The conducted tests demonstrated a substantial reduction in the isolation effect under 3D excitation, even in the horizontal plane, while the vertical response of the structure increased significantly due to higher mode effects. Therefore, it is imperative to adopt a comprehensive three-dimensional approach for seismic input analysis and support device design.

## EXAMPLE OF AN EFFICIENT 3D SEISMIC PROTECTION SYSTEM

Spring elements with helical steel springs show linear-elastic behaviour in both horizontal and vertical directions. An example for a typical spring device is shown in Fig. 5. There is nearly no dependency between the horizontal and the vertical stiffness of the spring devices. The horizontal stiffness is equal for both horizontal directions. Thus, their numerical description is comparatively simple and the behaviour of the structure on these devices can easily be assessed. The elements are carrying the dead weight of the structure and are designed to have sufficient safety margin to bear also additional loads (in both horizontal and vertical directions) from seismic excitation or other load cases. There is no deviation between the static and dynamic characteristics of the steel springs.

The springs and respectively spring elements range in bearing capacity, horizontal and vertical stiffness properties, and ratio between vertical and horizontal stiffness. These parameters can be adjusted to accommodate project specific requirements, as the design of the support system depends on the corresponding target performance of the structure. The vertical natural frequency F can be determined in a simplified way from the static compression of the springs by dividing 5 by square of "z". Where F is the vertical frequency in [Hz] and z is the vertical deflection in [cm]. Thus, a vertical static deflection of 10 mm corresponds to a vertical frequency of 5 Hz and a deflection of 250 mm results in a frequency of 1 Hz. Larger deflections (in other terms: lower frequencies) require taller springs and usually more springs to support the same load and hence, result in higher costs. As a consequence, it is strictly recommended to carefully determine the required frequency, depending on the project specific requirements.

As many NPP structures (e.g. equipment, machinery) are already elastically supported on spring elements for vibration isolation and soil subsidence protection, it is an important advantage that they can be used for seismic control too as mentioned in Siepe and Nawrotzki (2015). Thus, in seismically prone areas viscous dampers are arranged in parallel to the aforementioned spring units. This layout yields a larger damping ratio in the dominant mode shapes. This strategy is often combined with an optimization of the stiffness ratio of the springs. The viscous damper supplies high damping forces, which are high velocity-proportional. The properties of these devices can be described by the damping resistance values in all spatial directions. The devices, installed beside the spring elements, have the task to absorb the kinetic energy. The implementation of them yields an increase of structural damping and they serve as a displacement limitation of the structure and the devices themselves. Fig.5 shows typical elements.

Figure 5. 3D seismic protection system (viscous damper (left side) & prestressable spring unit (right side).

The basic principles of the proposed 3D system can be described as follows. The arrangement of the spring elements leads to a change of the mode shape of the supported structure and to a reduction of the dominant frequency, or in other terms to an elongation of the fundamental period of the system. Depending on the details of the seismic input, this frequency decrease could reduce the seismic demands by more than 60 %. In general, reducing frequencies creates larger relative displacements. Therefore, it is often required to find an optimum between the reduction of seismic accelerations and the ensuing displacements. The viscous dampers serve to increase the damping and to limit displacements. The increase of structural damping from 5 % to 20 % causes a reduction of absolute accelerations, structural stresses and displacements in a range of about 35 % according to table 18.7-1 of ASCE (2022). In an optimum case the reduction of frequencies is combined with the increase of damping. The theoretical investigations of the efficiency of such a system have been verified by experimental investigations by Rakicevic et al. (2006) and by a notable building project in Mendoza, Argentina. Two identical apartment buildings were commissioned in 2004. The first building was constructed with a conventional "fixed-base" foundation, while the second, adjacent building was supported by a 3D Base Control System (BCS). Stuardi et al. (2008) showed that the acceleration values at the base-controlled building were reduced by more than 70% compared to the unprotected building during a real seismic event. As a summary some principle 3D system parameters are provided in Table 3.

Table 3: Main characteristics of the presented 3D seismic protection system.

| Topic | 3D System | Comment |
|---|---|---|
| Horizontal stiffness | Low | Frequency of about 0.5 to 2.0 Hz |
| Vertical stiffness | Low - medium | Frequency of about 1.0 to 3.0 Hz |
| Horizontal acceleration | Low | |
| Stress / Strain level | Very low | |
| Vertical efficiency | High | |
| Displacement | Medium | |
| Vertical soil reaction | Medium | |
| Higher modes | Smooth effect | Increase of damping |
| Exchange of devices | Easily possible | |
| Bearing capacity | Medium – high | |
| Vibration isolation / protection against structure borne noise | Yes (integrated) | Horizontal and vertical frequencies |
| Aging / design life | OK | Experience in NPPs |
| Adjustment / levelling of structure / soil settlement | Standard procedure | Adding/removing steel shims |
| Control / levelling of forces | Easily possible | |
| Uplift | Tension possible | Specific part to connect spring with housing |
| Fine-tuning of stiffness and damping / modularity | Yes | Separate hardware parts (springs, dampers) |

## CONCLUSION

Vertical ground motion is ever present in seismic events. Addressing seismic isolation with isolators that only allow for horizontal modification of modes, leaves vertical ground motion to possible amplification of accelerations in the structure and components. Following an overview and explanation of motivation for 3D seismic isolation systems a corresponding system is presented in detail.

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