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OPTIMIZED LAYOUT PROCEDURE FOR 3D SEISMIC ISOLATION SYSTEMS FOR STRUCTURES IN NPPS

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ABSTRACT

Since earthquakes do not only act in a horizontal direction but also in a vertical direction, it is becoming increasingly important to provide earthquake protection in all three spatial directions. The last severe earthquake in Turkey in February 2023 showed that very high accelerations also occurred in vertical direction. This contribution illustrates the application of 3-dimensional support systems for the earthquake protection of NPP structures. The focus is on the detailed description of the corresponding layout steps and on the efficiency of combined horizontally/vertically flexible support systems.

INTRODUCTION

The present article concentrates on 3D support systems consisting of helical steel spring elements, that are combined with viscous dampers. The spring devices support the structure and provide horizontal and vertical flexibility. The dampers generate damping forces in all spatial directions. These forces are highly velocity proportional. The dampers do not bear any static force. A typical example of these devices and their arrangement is given in Figure 1.

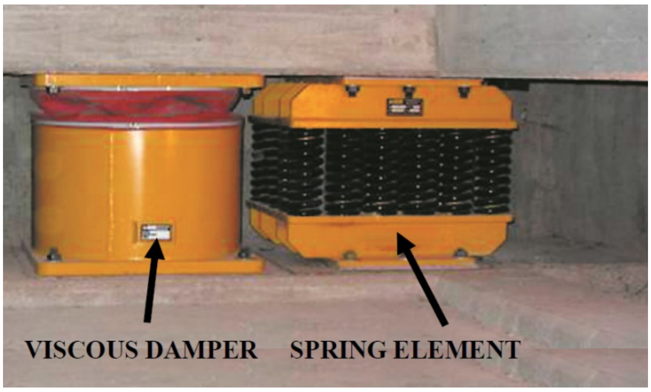

Figure 1. Spring and damper devices below reinforced concrete structure.

The described elements vary in the bearing capacity, in the horizontal and vertical stiffness properties, in the ratio between vertical and horizontal stiffness, in the damping resistance values and in the required possible stroke, as described in Siepe and Nawrotzki (2015). Thus, usually each project respectively structure requires a close look on the choice of elements. The general layout procedure consists of several steps – see also Nawrotzki et al. (2022). The present contribution deals with the further optimization and detailed explanation of these steps.

The theoretical basics are then illustrated with a practical example. In parallel to the design steps for the seismic protection system itself, the design and qualification of the overall system need to be considered. Here, tests in particular, such as those described in Kostarev et al. (2019), play an increasingly important role.

Different structures in nuclear facilities might face different challenges. Beneath the requirement of ensuring vibration isolation efficiency the problem of settlement of the structure and seismic demands occur. Elastic support systems satisfy these tasks depending on site, structure and performance specific requirements. The following three tables (Table 1, 2 and 3) provide a summary of typical values for the main characteristics for such systems – to provide a starting point for new projects / investigations.

Table 1: Design criteria for projects in the application area of subsidence.

Characteristic		Comment
Vertical frequency [Hz]	< 2.0	lower stiffness leads to smaller changes of the support force
Horizontal frequency [Hz]	-	only sufficient stability / strength is required
Damping ratio [%]	-	damping not required as settlement is a static load case

A typical view of corresponding spring elements is given in Figure 2. Steel shims are arranged below the spring units to keep the height of the supported structure. Building subsidence and differential soil settlements occur in many regions worldwide. The corresponding reasons and the expected soil motion may be different from case to case. Mining areas are one example for dangerous sites but also existing structures may be concerned by nearby excavation activities, e.g. by drilled tunnels for the expansion of traffic lines. Another source of settlement problem are climatic changes. Under warmer climatic conditions the permafrost terrain would be vulnerable to subsidence, as mentioned in Stendel and Christensen (2002). As the permafrost currently underlies nearly one fourth of the exposed land area of the Northern Hemisphere, the corresponding settlement issues are an important topic.

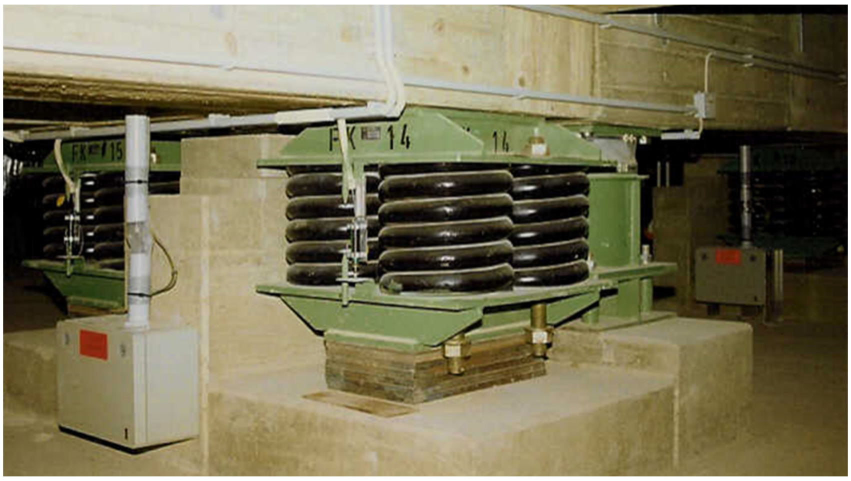

Figure 2. Spring elements and monitoring system below a cultural heritage.

Table 2: Design criteria for projects in the application area of vibration isolation.

Characteristic		Comment
Vertical frequency [Hz]	2.0 – 4.0	sufficient vibration isolation efficiency
Horizontal frequency [Hz]	1.0 – 3.0	typical values
Damping ratio [%]	~ 2.0 – 5.0	typical values for horizontal & vertical direction

The elastic support of buildings, equipment or machinery yields efficient vibration isolation. The vibration control could be defined as active, when the dissipation of vibration from machinery into the surroundings is prevented. On the other hand, passive vibration isolation protects structures against vibrations from outside sources such as machines, traffic vibration or even seismic excitation. It is possible to use elements with steel springs for both mentioned approaches. Figure 3 shows a typical elastic support system for machine foundations.

Figure 3. Combined spring damper devices below machine foundation.

The elastic support of machine foundations to achieve efficient vibration isolation has become "state of the art". Power plant machinery, like turbo generator sets, coal mills, feed water pumps, fans, diesel generator sets and other machine foundations benefit from this type of support to mitigate the transmission of operational vibration. The mentioned turbo generator sets represent one of the most important type of machinery in nuclear power plants. At the same time, this machinery is very sensitive and the design of their foundations requires special care and attention. Besides all functional requirements also seismically induced demands play a very important role for the layout. One of the first spring supported t/g sets was commissioned more than 45 years ago. As stated in American Society of Civil Engineers (2018), there is design and operating experience of several hundreds of installations with electrical capacities up to 1700 MW. Most of these systems consist of concrete frames or slabs, that directly support the high, middle and low-pressure turbine, the generator and related equipment. The direct substructure below the vibration isolation system may consist of reinforced concrete or steel.

In principle, the same elastic support systems with helical steel springs can be applied to improve the seismic behaviour of the structure. The layout criteria will be slightly different to the aforementioned parameters. In addition to yielding certain optimum frequencies it is essential to combine the devices with viscous damper to increase the structural damping. As described in Siepe et al. (2023) it seems to be quite helpful to have a look at some typical starting parameters. The stiffness ratio between vertical and horizontal stiffness of the device can be used to control the rocking part of the horizontal mode shapes.

Table 3: Design criteria for projects in the application area of earthquake protection.

Characteristic		Comment
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

This data can be considered for investigations of new projects. 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 occurring 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 ASCE 7-16 (2017). In an optimum case the reduction of frequencies is combined with the increase of damping. The theoretical investigations of the efficiency of the described system have been verified by experimental investigations by Rakicevic et al. (2006).

In summary, an elastic support system consisting of helical steel spring elements and viscous dampers allows the tuning of rigid body mode shapes into the low frequency range while also significantly increasing structural damping. This seismic protection strategy results in reduced seismic acceleration levels and corresponding structural advantages for the supported structures.

PROPOSAL FOR A LAYOUT PROCEDURE

A majority of seismic protection strategies still pays only attention to the horizontal effect of seismic events respectively the horizontal isolation by devices that provide horizontal low frequencies in combination with a vertically quite stiff support of the structure. The corresponding elements (e.g. lead rubber bearings, friction pendulum bearings) are well-known as Base Isolation System (BIS) and the corresponding arrangement procedures are known, too. Since structures will experience simultaneous horizontal and vertical excitations, the 3-dimensional effects should be considered. Upgrading a 2-dimensional support system to a system, that is effective in all three directions, might sound easy, but it requires a certain experience from the designer.

This section describes the layout procedure for a Base Control System (BCS) as an example. The arrangement of spring elements and dampers modifies the fundamental model characteristics of the structure, whereby the predominant frequency of the system is reduced and the corresponding mode shape exhibits a significant increase of damping. Thus, this approach complies with the general strategy, presented in the previous chapter. The following development steps are suggested to achieve desired performance of the elastic support system, the superstructure and the foundation / soil system below. They are based on Nawrotzki et al. (2022) and are slightly adjusted and enhanced with more steps.

Table 4: Layout steps for a 3-D elastic support system.

Step	Description
1	Choose target vertical support frequency.
2	Position spring elements between the superstructure and the substructure.
3	Check that springs have the same or similar vertical displacements under permanent loads. An uniform vertical displacement is recommended to ensure the chosen vertical frequency. If a certain tilting occurs, it can be reduced by adjusting the stiffness at each location or by changing the location of the devices. For a nearly rigid system rigid, the entire mass and centre of gravity are important for positioning of elements. For flexible structures the support positions are regarded individually. The required vertical stiffness values can be calculated for each support.
4	Choose the ratio between horizontal and vertical stiffness of the elements considering the seismic isolation requirements as well as the mechanical feasibility of the spring design.
5	Calculate all relevant frequencies and mode shapes of the whole system. Six rigid body modes exist for structures which are almost rigid. For flexible structures the elasticity of the superstructure plays an important role on the resulting frequencies and mode shapes.
6	Check all frequencies and mode shapes as well as of feasibility and capacity of suitable spring elements. If results are not favourable, repeat process from Step 1.
7	Choose the horizontal and vertical damping resistance of single dampers[*1]. Select the damper quantity & distribution below the superstructure in order to limit the seismic relative displacements to a demand amplitude and to reach an optimized isolation efficiency.
8	Check for damping ratios corresponding to the rigid body modes. 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 the structural seismic performance (accelerations, stress & strain levels, support reactions, displacements, etc.) by dynamic analysis for all requested seismic input levels. If performance targets are not achieved, start again at Step 7 or even at Step 1.
10	Check the feasibility/capacity of damper elements. If not feasible, start from Step 7.
11	Perform a detailed design of corresponding hardware. Analytically check the relative displacements and stress levels in these elements under the different seismic input levels.
12	Establish pre-qualification criteria for hardware (springs, spring elements, dampers) by static and dynamic testing according to current regulations.
13	Development of quality assurance plans for the production of the elements.
14	Documentation of manufacturing, production tests and other reports (quality assurance, factory acceptance tests, etc.).
15	Development of installation, inspection and maintenance instructions.
16	Support local activities, such as qualification, quality assurance procedures, and manuals for installation, inspection, adjustment, and replacement.

[*1] Note: The damping values could be taken from dynamic tests by evaluating the energy dissipation during one loop. Due to the low frequency range of the main modes the influence on the frequency change is very small and the aforementioned simplified model can be used.

CALCULATION EXAMPLE

The previously described layout steps are illustrated by a simplified example. The investigated structure consists of a rigid body with a length of 20 m, a width of 15 m and a total height of 10 m. The total spring supported mass is assessed with 1500 metric tons. Four devices are arranged below the structure, one at each corner. Assuming a rigid body behaviour, the structure will possess 6 eigenmodes and eigenfrequencies, as shown in Figure 4. As the spring devices exhibit a vertical and horizontal distance to the centre of gravity, several coupled modes shapes exist. For each horizontal direction there will be two translational mode shapes (rocking mode and pendulum mode) beneath the vertical mode shape and the rotational mode shape around the vertical axis.

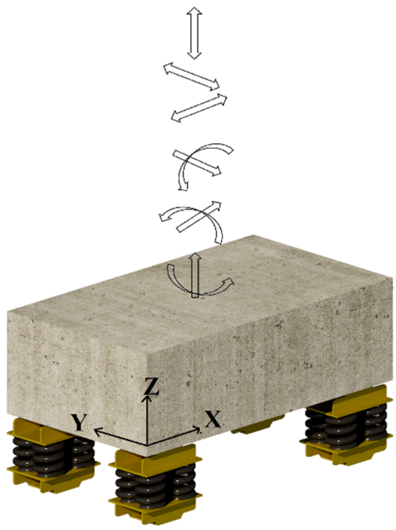

Figure 4. Degrees of freedom in a single mass system.

Three different sets of parameters (in terms of horizontal and vertical stiffness and damping resistance of the devices) are investigated to show the effect of some important layout strategies. The spring devices can be described with two parameters, the spring constants for the vertical and horizontal direction, respectively. For their numerical modelling, it is essential to use representative elements that do not introduce artificial effects into the model. Spring elements transfer vertical and lateral loads only. When the effect of dampers must be included, it is important to use a program (e.g. finite element software) that can appropriately model velocity-proportional dampers, or even more complex viscoelastic dampers. For the current example the dampers are described by their horizontal and vertical damping resistance values, as described in a previous chapter. The following Table 5 provides the summary of the chosen values.

Table 5: Overview of investigated models.

Parameter (Design value) of 1 device	Model 1	Model 2	Model 3
Horizontal stiffness [kN/mm]	14.7	92.0	13.0
Vertical stiffness [kN/mm]	14.7	92.0	92.0
Horizontal damping resistance [kNs/m]	390	1800	1800
Vertical damping resistance [kNs/m]	235	1200	1200

Having in mind a low frequency, the first idea for the target frequency (see Step 1 of Table 4) could be 1.0 Hz for the vertical direction. For the second model a larger vertical frequency was chosen. The third model considered a higher stiffness ratio. Table 6 provides a summary of the most important modal results.

Table 6: Modal results of 3 different models.

	Model 1	Model 2	Model 3
Rigid body mode shape	Frequency, Damping	Frequency, Damping	Frequency, Damping
Translation in x / rotation about y (rocking mode)	0.84 Hz, 5.9 %	2.10 Hz, 11.3 %	0.92 Hz, 38.4 %
Translation in y / rotation about x (rocking mode)	0.75 Hz, 5.0 %	1.89 Hz, 9.6 %	0.90 Hz, 36.5 %
Translation in z	1.00 Hz, 5.0 %	2.49 Hz, 10.2 %	2.49 Hz, 10.2 %

The seismic input (shown in Figure 5) in terms of elastic design spectra is defined according to American Society of Civil Engineers. (2017), assuming Ss = 1.4, S1 = 0.5, TL=8 and Class B.

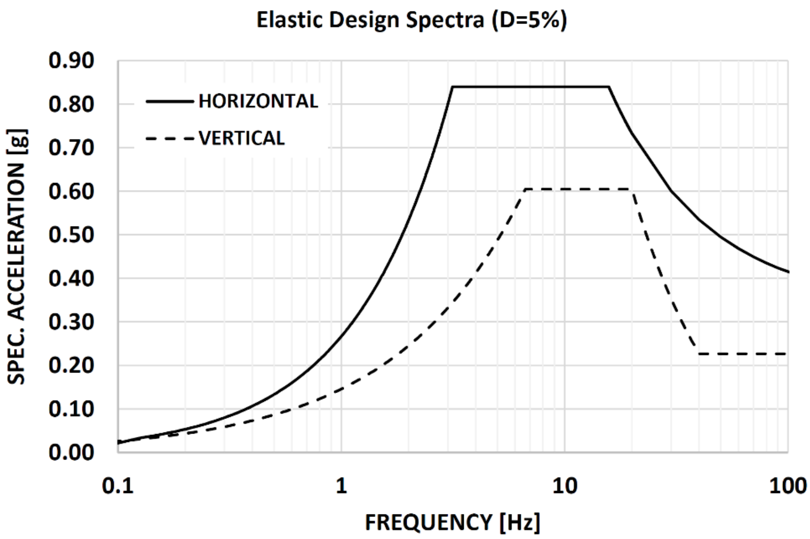

Figure 5. Seismic input.

The most important results of response spectrum analyses are presented in Table 7.

Table 7: Seismic results of 3 different models.

Results after superposition 100-30-30	Model 1	Model 2	Model 3
Horizontal relative displacement at spring device [mm]	50	17	42
Vertical relative displacement at spring device [mm]	70	22	12
Horizontal absolute acceleration at centre of gravity [g]	0.20	0.41	0.15
Vertical absolute acceleration at centre of gravity [g]	0.15	0.23	0.23

The results of the first model show quite large relative displacements. Thus, the corresponding devices would be quite complex and for beyond design cases the general feasibility might be questioned. Thus, the support system needs to be optimized. In a first step the vertical target frequency is increased to about 2.5 Hz. This helps to reduce the occurring displacements significantly, but yields an increase of absolute accelerations. To improve the accelerations and to reduce the rocking part of the horizontal mode shapes a stiffness ratio of 7 between vertical and horizontal stiffness is chosen. Figure 6 shows a typical spring element with a larger stiffness ratio. The vertical frequency remained unchanged. Now, the horizontal absolute accelerations are lower than for the first model. At the same time the vertical displacements of the devices are quite small.

The limitation and reduction of relative displacements of the devices and hence the supported structure is a very important target, which enables to simplify the design of the devices and avoid making special compensations for connecting the distribution systems of an isolated structure.

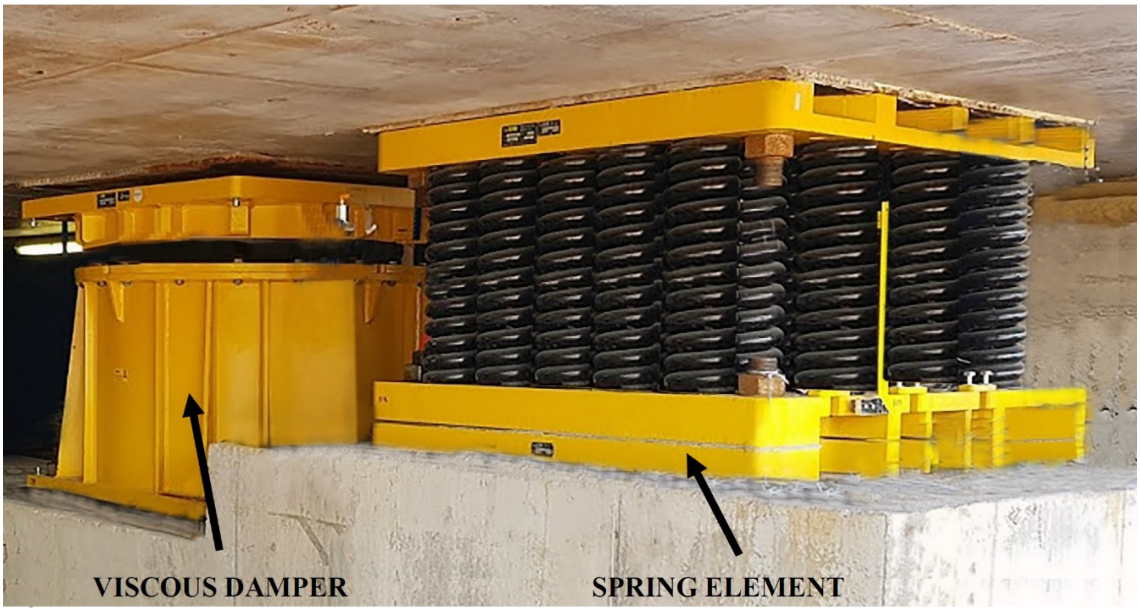

Figure 6. 3-D viscous damper and spring element with stiffness ratio 6.9 for heavy nuclear structures.

EXECUTED PROJECT IN A NPP AND OUTLOOK FOR NEW STRUCTURES IN NPPS

Spent fuel storage tanks in nuclear power plants are one example of very sensitive equipment. They require special attention in regard to their safety and related qualification. Structural acceleration should be kept to low values as the overflow of liquid is not acceptable and the integrated steel racks should not contact each other. Here, water leakage and subsequent release of radioactive substances must be avoided. Beneath seismic requirements it is also mandatory to consider additional extraordinary load cases like aircraft impact.

A corresponding project example with spring and damper devices can be found at a nuclear power plant in Switzerland. The main purpose here is not related to the reduction of structural stress or strain, but to the reduction of response acceleration. Waves on the water surface should not overflow the top of the pool walls. In this project the devices support a mass of approximately 6000 metric tons. The special parameters of the support devices lead to relatively low structural frequencies and correspondingly high damping which reduces acceleration and avoids the overflow of water.

Regarding new projects it should be kept in mind that there are more than 100 buildings worldwide nowadays supported on spring elements. In most of these cases the elastic support is required to ensure vibration isolation efficiency, e.g. if there is a train passing by. The corresponding 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 earthquake effects, as already described in this contribution.

Thus, it seems absolutely possible to install also a complete NPP building or parts of a nuclear facility on top of a 3-D elastic support system with springs and dampers. Corresponding numerical studies were performed, and in Nawrotzki et al. (2013) it was shown that the proposed control system leads to a significant reduction of the accelerations, base reactions and the values of the floor response spectra. Due to these positive results it is recommended to investigate the application of a 3-dimensional Base Control System for practical application in NPP structures – under consideration of the aforementioned layout steps.

CONCLUSION

The presented schematic of the design principles and development steps for a 3D seismic control system generally shows a methodical approach for a successful implementation. However, the chosen parameters have to be defined depending on the project specific requirements. Therefore, cooperation between designers, suppliers and end users is crucial to avoid misunderstandings and lengthy iterations in the selection of system parameters.

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