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Division V

3D SEISMIC ISOLATION SYSTEMS FOR THE NUCLEAR INDUSTRY LAYOUT, DESIGN & QUALIFICATION

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ABSTRACT

This contribution presents general layout procedures, important design issues as well as general remarks regarding the qualification of the corresponding devices. The complete layout process for an exemplary 3D earthquake protection system is also described. Lastly, corresponding details of executed projects are discussed; including qualification by full-scale testing of 3D devices under different performance levels.

INTRODUCTION

Nuclear islands, reactor and auxiliary buildings and similar seismic category 1 structures in nuclear facilities must be protected against seismic demands. The most common seismic isolation systems consisting of rubber bearings (e.g. LRBs), and friction pendulum bearings (FPS) are effective for protection against horizontal earthquake excitation. However, vertical ground motion and other possible dynamic impacts on the structure should be included in the performance assessment based on internationally recognized standards as ASCE, etc. Therefore, systems have been developed that work in all three spatial directions. Together with the well-known horizontal systems mentioned above, these 3D isolation systems are briefly described in the IAEA TECDOC-1905 (2020).

At first, adding vertical elasticity may not seem that difficult, but there are some important details to consider. After defining the vertical target frequency, the arrangement and stiffness parameters of the devices should be chosen to achieve the corresponding vertical displacement under permanent loads. Here, it is important to consider the elasticity of the sub and superstructures, if it has a significant influence on the resulting frequencies and mode shapes. This first step is followed by a partly iterative process until the desired performance of the 3D seismic protection system, the superstructure and the foundation / soil system is achieved. In general, the procedure requires an experienced designer and willingness to work with the manufacturers as early as possible in the project development process. The horizontal and vertical stiffness properties, as well as the corresponding load and displacement capacities of the devices must be discussed to ensure design and production feasibility.

Already during the initial design of a 3D isolation system, all important load scenarios, e.g.: BDBE (Beyond Design Basis Earthquake), CS (Clearance to the Stop) and FM (Failure Mode), must be considered in addition to the “basic” SSE (Safe Shutdown Earthquake) case. This not only includes the calculations but also the planning of the corresponding tests and quality assurance measures. Qualification tests are one of several important topics to be addressed with the regulator at an early project stage. For example, if newer test methods are applied, that allow a test of full-scale devices subjected to dead load and seismic displacements as described in Nawrotzki et al. (2019), and described later in this paper.

LAYOUT OF A 3D SEISMIC PROTECTION SYSTEM

The layout of a suitable seismic protection system requires experience from the designer. This section describes the corresponding procedure for a Base Control System (BCS) as an example. These systems consist of spring elements, which are arranged below the base plate of the structure. Additionally, highly efficient viscous dampers are also arranged. The system is flexible in the horizontal directions, but possesses also vertical elasticity. The dampers supply absorption forces in all spatial directions. The implementation of spring elements and dampers modifies the fundamental model characteristics of the structure, whereby the predominant frequency of the system is reduced (=elongation of the fundamental period) and the corresponding mode shape exhibits a significant damping ratio increase. A typical view of such a system is shown in Figure 1.

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

When selected appropriately the BCS elements will significantly improve the seismic performance of the 3D base isolated structure. It is very important to choose, arrange, design, qualify and install the elements in an appropriate manner. Thus, it is recommended to contact the manufacturer of the devices as early as possible in the project development process. This approach will help to reduce the numbers of iterative steps and will ensure the general feasibility of the desired element parameters. The following development steps are suggested to achieve desired performance of the BCS, the superstructure and the foundation / soil system below:

Step 1: Choose the target vertical support frequency based on the properties of the structure, the sub-structure and requirements of the desired performance of the BCS under the given seismic input.

Step 2: Position spring elements level between the superstructure and the substructure (e.g. pedestals on base mat).

Step 3: Check that 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. Figure 2 shows a simplified sketch. The picture on the left side shows a certain tilting. This can be reduced by adjusting the spring stiffness at each location or by changing the location of the spring devices.

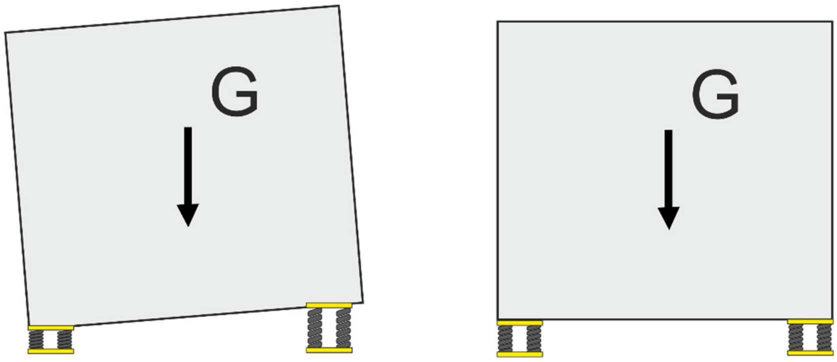


Figure 2. Tilting (exaggerated) of structure (left) due to non-uniform vertical displacement, optimized layout (right).

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.

Step 4: Choose the ratio between horizontal and vertical stiffness of the spring elements considering the seismic vertical and horizontal isolation requirements as well as the mechanical feasibility of the spring design.

Step 5: Calculate all relevant frequencies and mode shapes of the entire system. For structures which are almost rigid six rigid body modes exist. For flexible structures like many conventional buildings, the elasticity of the superstructure plays an important role on the resulting frequencies and mode shapes.

Step 6: Check 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 *Step 1*.

Step 7: Choose the horizontal and vertical damping resistance of single dampers. Select the damper quantity & distribution below the superstructure in order to limit the BCS seismic relative displacements to a demand amplitude and optimized isolation efficiency.

Step 8: Check for damping ratios corresponding to the rigid body modes; 6 mode shapes & frequencies exist. 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.

Step 9: Check the structural seismic performance (acceleration, stress & strain levels, support reactions, displacements, etc.) by dynamic analysis for different seismic input levels (DBE, BDBE, CS, etc.). Use 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 *Step 7* or even at *Step 1*.

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

Step 11: Perform a detailed design of corresponding hardware, i.e. spring elements and dampers. Analytically check the relative displacements and stress levels in these elements under the different seismic input levels.

Step 12: Establish pre-qualification criteria for hardware (springs, spring elements, dampers) by static and dynamic testing according to current regulations, at least under DBE, BDBE conditions.

Step 13: Develop production quality assurance programs.

Step 14: Develop installation, inspection and maintenance manuals.

The designer should already have an insight into steps 12 and 13 during the first steps of the layout procedure. Coordination with the manufacturer of the spring and damper elements, the customer and, if necessary, authorities or external test institutes is strongly recommended, and in most cases required. Depending on the project specific requirements, certain qualification procedures have to be used. Helical steel springs can be calculated and designed according to DIN EN standards. Prototype tests are also possible. Calculating the damper properties is generally not possible, usually requiring the performance of prototype tests to ensure and verify the design values of these devices. Special tests may be required to consider the influence of different temperature conditions, humidity, corrosion and/or radiation. For nuclear facilities it is essential to choose a suitable damper in regard to radiation effects. Figure 3 shows a typical example of viscous dampers in an NPP.

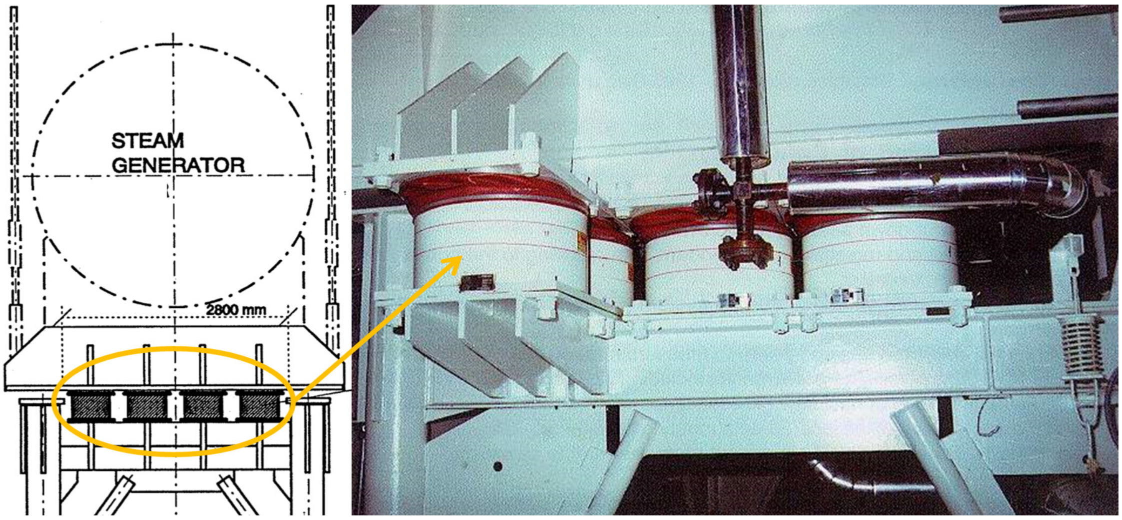


Figure 3. Seismic Protection of Steam Generator in NPP Bohunice, Slovakia.

In addition to the required documents regarding the general qualification of the supplier of spring and damper devices it is at least mandatory to provide Quality Assurance Plans. These plans have to been taken as a basis for ensuring the quality assurance of the devices. The general qualification could consist of the following components:

- prototype testing / qualification,
- production testing / quality assurance,
- certification of Quality Management Standard,
- certification of Environmental Management Standard,
- certification of Occupational Health and Safety Management System,
- documentation of the delivery capacity,
- documentation of the required test equipment for the spring elements and damping devices,
- test stands required for pre-qualification / and quality assurance.

BUILDING IN ARGENTINA

The stepwise procedure for the layout of seismic protection system, as described in the previous chapter, was applied successfully to many projects during the last decades. In general, each structure and corresponding project specific conditions (in terms of seismic input and requirements) are different. For a wide variety of structures (buildings, machine foundations, equipment) the parameters of the seismic protection devices are optimized. More information about the optimization procedure can be found in Nawrotzki and Siepe (2017). Based on the gained experience it is feasible to summarize some general design criteria. These are presented in Table 1.

Table 1: Layout criteria for earthquake protection projects.

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 motions

A corresponding example is the project of two identical apartment buildings, built in 2004 at Mendoza, Argentina. The first building consists of a conventional “rigid” foundation, and the second, adjacent building is supported by a Base Control System. Figure 4 shows the structures. Both buildings consist of three floors of reinforced concrete and masonry infill. After commissioning the National Technological University of Mendoza installed seismic accelerometers in both buildings. It has been possible to directly compare the seismic responses of both buildings during the same seismic excitation. Figure 4 presents the measured results at the roof of each building during an earthquake in 2005 with a peak ground acceleration of about 0.12 g.

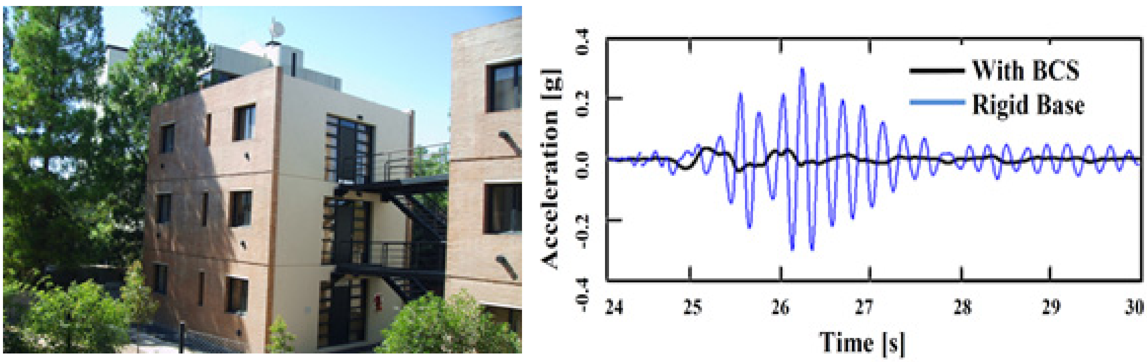


Figure 4. View of buildings and measured absolute accelerations at roof levels.

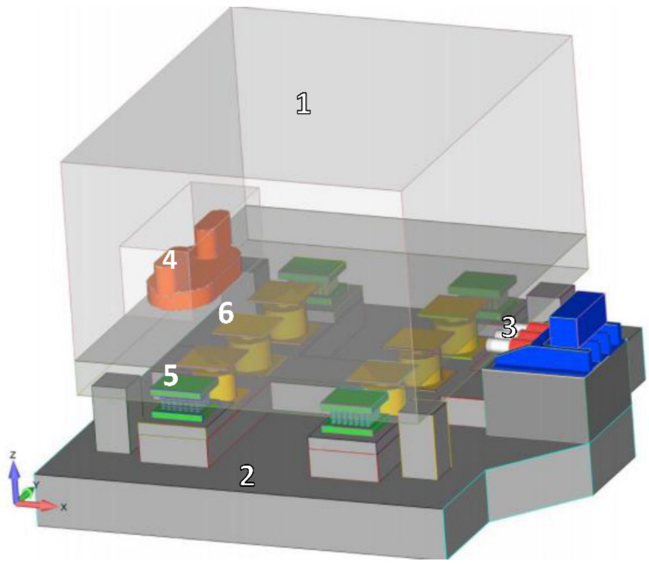
The efficiency of the BCS can be seen by comparing the measured results. The horizontal maximum acceleration at top of the building was reduced by more than 70 %. The measured data was also used to adjust the initial analysis model. It is shown in Stuardi et al. (2008) that similar to the acceleration reduction also the corresponding structural responses like internal forces and subsoil reactions could be reduced significantly.

TEST STAND IN ST. PETERSBURG

The project specific developments and solutions are backed with theoretical as well as practical investigations. More than 15 years ago extensive shaking table tests have been performed at IZIIS (Institute of Earthquake Engineering and Engineering Seismology) in Skopje, North Macedonia. Their biaxial shaking table is able to generate an acceleration input up to 3.0 g for the horizontal direction, as well as a vertical acceleration input up to 1.5 g. These values are applicable for zero pay load. The 5.0 x 5.0 m table possesses a maximum pay load of about 40 metric tons. A five story, three bay steel frame model with a total mass of about 24 metric tons has been tested with and without Base Control System on the described shaking table.

The efficiency of the mitigation system has been studied by simulating a set of ten different earthquake records for both test-configurations. Evaluating the large number of recorded time history responses in terms of absolute accelerations, axial and bending strain at different locations of the structure it can be concluded that the BCS reduces the structural responses by more than 50 % compared to the unprotected structure. More detailed information can be found in Rakicevic et al. (2006).

Beside the tests on typical shaking tables it is nowadays also possible to test elements of a BCS and/or other seismic isolation devices at a new test stand, erected in St. Petersburg, Russia. Here, a special inverse test rig (SIST) was developed for test performance of real structures with seismic isolation systems at full scale. In contrast to typical shaking tables, the inverse approach implies that the substructure is not shaking but the superstructure is shaking at its natural frequencies with amplitudes resulting from gravity and full seismic loading. The principle of the general test-setup is shown in Figure 5.



1. **Building Model (Variable Mass Concrete Structure 1000 to 3000 t)**
2. **Foundation on a medium soil conditions**
3. **Hydraulic Pusher System with a fast load release function**
4. **Mechanical Vibrator**
5. **Isolators**
6. **Dampers**

Figure 5. Configuration of the test stand.

The test setup consists of a superstructure with a mass between 1000 and 3000 metric tons and a hydraulic system that is able to push the structure to the desired maximum displacement and ensures a quick-release of the pushing mechanism to allow free movement of the supported structure. The superstructure placed on 4 isolators and a variable number of damping devices. Figure 6 shows the setup at the site in St. Petersburg before the first tests were performed in December 2017.

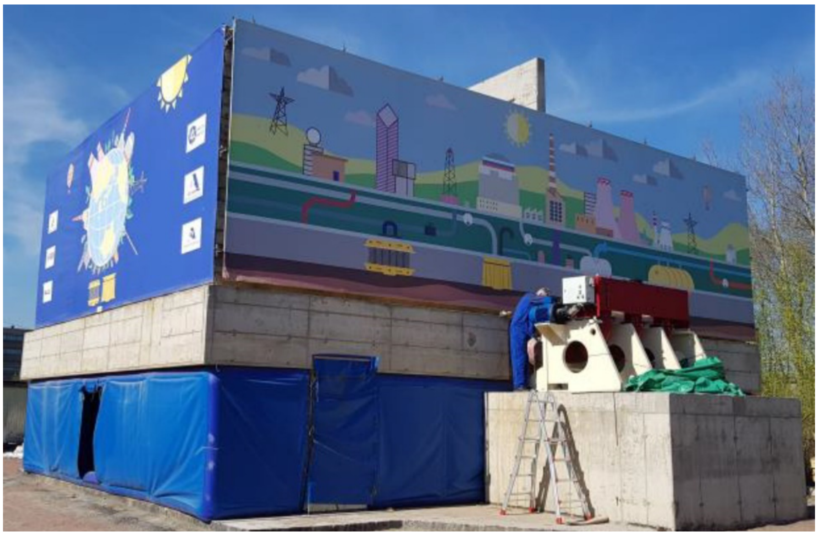


Figure 6. General view of SIST.

The initial tests verified the general functionality and operability of the test rig. Afterwards extensive tests of the 3D Base Control System were performed. The results show that the spring elements and viscous dampers provide previously defined optimal parameters to the superstructure, as presented in Kostarev et al. (2018). The corresponding test series was accompanied by previous individual static and dynamic testing of the devices at different test facilities, as discussed in Kostarev et al. (2019). The test rig was presented to the public during the 16th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structure in St. Petersburg in 2019.

CONCLUSION

The presented outline of layout principles and development steps for a 3D seismic control system generally shows a methodical approach towards a successful implementation. However, the chosen parameters are subject to the frequency content of horizontal and vertical ground shaking, as well as the displacement capacities of the selected devices. Hence, collaboration between designers, suppliers and end users is critical to avoid tedious iterations in selecting system parameters. Furthermore, a typical example of a BCS protected structure was discussed, where the calculated and measured responses show the applied control system yields a very significant reduction of seismic demands. The use of a BCS and the proposed layout process should be further investigated for practical application in Nuclear Facilities.

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