Comparative Analyses of a Nuclear Island on Linear and Non-Linear Aseismic Bearing Pads

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SUMMARY

As part of a feasibility study, a Nuclear Island resting on a foundation incorporating a double mat system with interposed aseismic bearing pads, which isolate the plant structures from severe horizontal motions, was analyzed for Safe Shutdown Earthquake excitation. The Nuclear Island comprises six Category I buildings constructed on independent upper mats resting on aseismic bearing pads. The six buildings are joined at the upper mat level by reinforced concrete structural connections which impose an in-phase horizontal vibration of the buildings during a seismic event. Two seismic isolation schemes were considered in the analyses. The first foundation included elastomer bearing pads attached directly to the upper mat and, through pedestals, to the common lower mat. The pad distribution and thickness were chosen so that the natural frequency of the Nuclear Island is equal to 0.6 Hertz for horizontal vibration. In the second scheme, sliding elements with a friction ratio of 0.2 were placed just below the upper mat and the pads were designed so as to achieve a natural frequency of the Nuclear Island equal to one Hertz. To investigate the response of the Nuclear Island when subjected to the design earthquake, a three-dimensional model of the Island and of its foundation was developed. The three-dimensional model included the building super-structures, the structural connections between the individual building mats, the aseismic interface and lumped parameter soil-structure interaction impedances.

The dynamic linear analysis was performed for the non-sliding pads utilizing the computer code DAPSYS and consisted of mode frequency analyses and modal superposition. The code ANSYS was used to perform the non-linear analyses by numerical integration of the equations of motion for the sliding pad scheme. In both analyses, the model was subjected to a postulated seismic event, represented by two horizontal and one vertical synthetic accelerograms matching the USNRC Regulatory Guide 1.60 Response Spectra, for a peak ground acceleration of 0.26g. The comparative behavior of the two seismic isolation schemes is presented in terms response spectra at various locations in the models, forces and moments in the structural mat connections, displacements of the upper mats, and deformation of the pads. For the Nuclear Island configuration and the seismic excitation considered, the analyses indicated that introduction of sliding pads reduces the acceleration level and overall response of the Nuclear Island structures. In particular, the horizontal displacement of the structures and the shear forces in the upper mat structural connections were significantly reduced by the use of sliding pads.

1. Introduction

Seismic foundation isolation schemes are an attractive solution for the design of nuclear power plants in seismic areas. By reducing the horizontal accelerations, especially in the high frequency range, they allow the use of a standardized design on sites with significant seismicity. Two solutions have been adopted to date to isolate the most important buildings of nuclear power plants during a postulated Safe Shutdown Earthquake (SSE). The first isolation scheme which was utilized in France (Cruas Nuclear Power Plant) includes elastomer bearing pads while the second scheme (used at the Koeberg Nuclear Power Plant in South Africa) also comprises sliding elements.

It s generally expected [1] that the first scheme will perform satisfactorily for peak ground accelerations up to about 0.23 g and broad design spectra e.g. the USNRC Regulatory Guide 1.60 [2].

This paper presents a comparison between these two isolations schemes for which dynamic analyses were performed as part of the feasibility study of a nuclear power plant to be designed for a peak ground acceleration of 0.26 g.

2. Foundation Conditions and Seismic Input

The soil profile considered for the feasibility study consisted of three main horizons:

- An upper deposit of basalt extending to a depth of 26 meters below foundation level with a shear wave velocity increasing from 1,100 to 1,800 meters per second,
- A sedimentary deposit consisting of about 80 percent clay, extending to a depth of 98 meters, with a shear wave velocity of 940 meters per second, and
- A deep deposit of andesite with a shear wave velocity of 1,500 meters per second.

The Safe Shutdown Earthquake (SSE) considered in the transient dynamic analyses for this nuclear power plant was defined by the horizontal and vertical response spectra of the USNRC Regulatory Guide 1.60 scaled to a peak ground acceleration of 0.26 g. Synthetic acceleration time histories developed [3] to match the design response spectra, at five percent damping, were used for this study.

3. Structural Arrangement of the Nuclear Island

The study considered the arrangement consisting of six Category I buildings resting on an aseismic interface. For both isolation schemes, this aseismic interface [4] includes reinforced elastomer bearing pads. The upper mat complex, which supports the Nuclear Island buildings, comprises the individual building mats linked together by means of stiff reinforced concrete connections. The lower mat, which is founded at a depth of about 11 meters below the final plant grade, is surrounded by a retaining wall. The Turbine Halls and other non-Category I buildings are placed adjacent to the Nuclear Island and are directly founded on the rock with conventional foundation schemes.

The distribution of the aseismic bearings under the six buildings of the Nuclear Island is shown in Figure 1. The aseismic bearings are composed of two, four, six or eight reinforced elastomer pads, each of which is an integral element of horizontal layers of elastomer alternating with metal plates. The purpose of the metal plates is to provide confinement of the elastomer and thereby minimize the shearing stresses in the elastomer caused by the vertical loads. In the second isolation scheme, a sliding bearing is located just above the elastomer pad. The lower plate is attached to the elastomer pad, whereas the upper one is attached to the upper mat. The two plates are made of special alloys to achieve a constant coefficient of friction approximatively equal to 0.2.

This arrangement provides an element with high vertical stiffness and low stiffness to horizontal shear forces. The effects of the elastometer pads are:

- To control the horizontal stiffness of the foundation such that the natural frequency of the horizontal structure-foundation mode is well below the frequency range for high amplification of seismic motion.

- To impose an almost pure horizontal translation mode on the structure, with little rocking participation.

- To minimize or eliminate participation of higher structural modes by filtering the higher frequency earthquake input motions.

- To transform the controlling seismic design parameter from acceleration into displacement by forcing the plant frequency to be in the low frequency portion of the design response spectrum.

The additional effect of the sliding bearings is to limit the maximum horizontal shear force transmitted to the buildings. In this manner, the horizontal accelerations are significantly reduced at the price of small residual displacements which can be corrected if slippage should occur.

4. Development of Analytical Models of the Nuclear Island

To investigate the response of the Nuclear Island when subjected to the design earthquake (SSE), a three-dimensional model of the island and of its foundation was developed. The structures of the Nuclear Power Plant which were included in the model are shown in Figure 1. The analytical model developed for the purpose of computing the seismic response is composed of the following components :

- Building superstructures
- Structural mat connections
- Aseismic interface
- Soil-structure interaction parameters

Each of these elements are discussed in the following subsections.

4.1 Building Superstructures

For each building, lumped masses, and lumped moments of inertia at the floor locations, were used to represent the mass of the floors, walls and equipment, while the walls between floors were modeled as beam elements (Figure 2).

4.2 Structural Mat Connections

In order to prevent relative displacements between the upper mats during the postulated seismic event, structural connections are provided between adjacent buildings. These connections comprise a solid concrete slab spanning from one building to the other and extending along the entire interface between the buildings being connected. Owing to the reinforcing effect of the building superstructures on their own slabs, the building mats were assumed to be rigid and the connections between them were given the ability to resist all possible relative motions between the buildings they link. The structural connections were therefore represented in the mathematical model as 12 by 12 stiffness matrices connecting the lowest nodes of the stick models of the connected structures (Figure 2).

4.3 Aseismic Interface

For both isolation schemes, the upper and lower mats of the building foundations are interposed by elastomer pads, mounted on concrete pedestals, cast integrally with the bottom mat (see Figure 1). The elastomer pads are distributed so as to give a uniform vertical working stress of 5.5 MPa under static conditions. The total thickness of elastomer is thirteen and five centimeters for the non-sliding and the sliding isolation schemes, leading to natural frequencies of 0.6 and one Hertz, respectively.

The stiffness and damping of the complete group of pads beneath each building were represented by six springs and six dampers (three translational and three rotational). These lumped parameters were obtained from the springs and dampings at each pedestal and their distribution with respect to the center of the building. For the sliding scheme, special sliding elements were placed in series with the springs (Figure 2).

4.4 Soil-Structure Interaction Parameters

In order to take proper account of the interaction between the structures and the foundation soils during earthquake loading, the foundation impedance of the Nuclear Island was determined according to the following steps:

- Establish a design soil profile with pertinent zero-strain dynamic properties for the different layers.

- Estimate the reduction in shear modulus and the material damping ratio of the substrata caused by "free-field" earthquake motion using the computer code SHAKE [5].

- Calculate the zero-frequency (static) impedance matrix of the global Nuclear Island foundation and its variation using frequency using the methodology developed by Kausel [6].

- Based on the above, calculate each term of the global dynamic stiffness and damping matrices applicable to the soil-structure interaction frequency of each mode of vibration.

- From static elastic half space theory, redistribute the stiffness under each building so that the global behavior of the Nuclear Island foundation is properly represented. This was achieved by means of a higher order winkler (HOW) model which introduces coupling between adjacent buildings (Figure 2) so as to simultaneously account for translational and rotational interaction [7]. Similarly, redistribute, for each mode, the global damping matrix under each building foundation.

5. Dynamic Analyses of the Nuclear Island

The mathematical model of the buildings, the structural connections, the aseismic interface and the foundation represented in Figure 2, was subjected to a linear analysis for the non-sliding isolation scheme and a non-linear analysis for the scheme with sliding bearings. These analyses are described in the following subsections, while the results are presented and compared in Section 6.

5.1 Non-Sliding Isolation Scheme

The dynamic linear analyses for the non-sliding pads which were performed utilizing the computer code DAPSYS [8], consisted of mode frequency analyses and modal superposition with composite modal damping. The composite modal damping is computed in DAPSYS as a weighted average of structural and soil damping [9], using the strain energy stored in the respective components as the weighting factor. This approach distinguishes the hysteretic nature of the structural and soil material damping from the viscous nature of the radiation damping. The modal analyses covered frequencies up to 30 Hertz and the response of each mode was integrated with a time step of 0.01 seconds.

5.2 Sliding Isolation Scheme

The ANSYS computer Code [10] was used for the transient non-linear analyses in this study. In order to obtain better computational efficiency, the substructuring technique of the finite element method was utilized for the superstructure and the upper mat of the Nuclear Island. The stiffness, mass, damping and gravity load vectors of this superelement were then stored on a computer file. The complete model of the plant was then developed by connecting the substructure described above to fixed supports under each building through the mathematical representation of the aseismic pads and of the soil impedance.

The damping of the superelement was introduced by means of Rayleigh damping while the damping of the aseismic pads and of the foundation soil were input as damping matrices.

Transient dynamic solutions were obtained by numerical integration of the equations of motion using the Houbolt numerical integration scheme which is unconditionally stable for all integration time steps. An integration time step of 0.005 second proved adequate for the non-linear analyses.

6. Presentation and Discussion of the Results

In order to investigate the performance of the aseismic foundation-structure systems and assess their feasibility, the following results were obtained from the dynamic analyses :

- o Floor response spectra at the base and top of the buildings.
- o Relative displacements of the upper mats, magnitude of slippage (if any), vertical and shear stress in the aseismic bearings.
- o Forces and moments in the structural connections between buildings.

The response spectra at the base of the Reactor Building are shown in Figure 3 and compared to the design ground response spectra. The horizontal spectra illustrate the filtering effect of the aseismic isolation schemes in the high frequency range. The responses are very sharp and of similar magnitude near the fundamental frequencies of 0.6 and one Hertz for the non-sliding and sliding schemes, respectively, and are nearly flat above frequencies greater than about three time the fundamental frequencies. The maximum horizontal accelerations are reduced from 0.25 g to 0.23 g when sliding is permitted. Owing to the high vertical stiffness of the elastomer pads, the vertical spectra are virtually identical.

The horizontal relative displacement and rocking time histories at the base of the Reactor Building are given in Figure 4. The horizontal displacements and the torsion of the nuclear island for non-sliding pads are about twice those of the sliding pads. On the other hand, the rocking is only slightly larger for the non-sliding scheme. From the linear analysis (non-sliding scheme), the displacements and load time histories acting in each individual pad were obtained. Special attention was given to the distortion, the vertical stress and the ratio (H/V) of the horizontal to the vertical load acting in the pads. These results show that the maximum relative distortion is equal to 1.4 in all pads, that some pads experience an uplift and that large values of H/V (on the order of 0.35) exist, especially in the pads located along the periphery of the island. The results of the non-linear analyses (sliding scheme) where H/V is limited to the friction coefficient of the sliding plates (0.2) show that the maximum pad distortion is reduced to one.

Finally, the time histories of vertical shear force and bending moment acting in a 7.2 meter linear segment which was used to represent the circular structural connection between the Electrical and Reactor Buildings at the location indicated in Figure 1 are given in Figure 5. The sliding scheme performs again more favorably especially for the shear force which is reduced by a factor of about two.

7. Summary and Conclusions

The performances of two schemes for the seismic isolation of a nuclear island have been evaluated and compared for a seismic motion matching the USNRC response spectra with a maximum ground acceleration of 0.26 g. The study has shown that for the soil conditions, the structural arrangement and the postulated seismic event considered, the aseismic foundation scheme including sliding plates was preferable. Also, the non-sliding isolation scheme which required a high thickness of elastometer yielded large relative distortion (1.4) in the pads and local uplift which would have required special techniques for design and construction of the pads.

This study has demonstrated that even a slight increase in acceleration level, over that considered to be acceptable, for a non-sliding isolation scheme, is sufficient to show definite advantages for the sliding plate isolation pads in terms of structural response.

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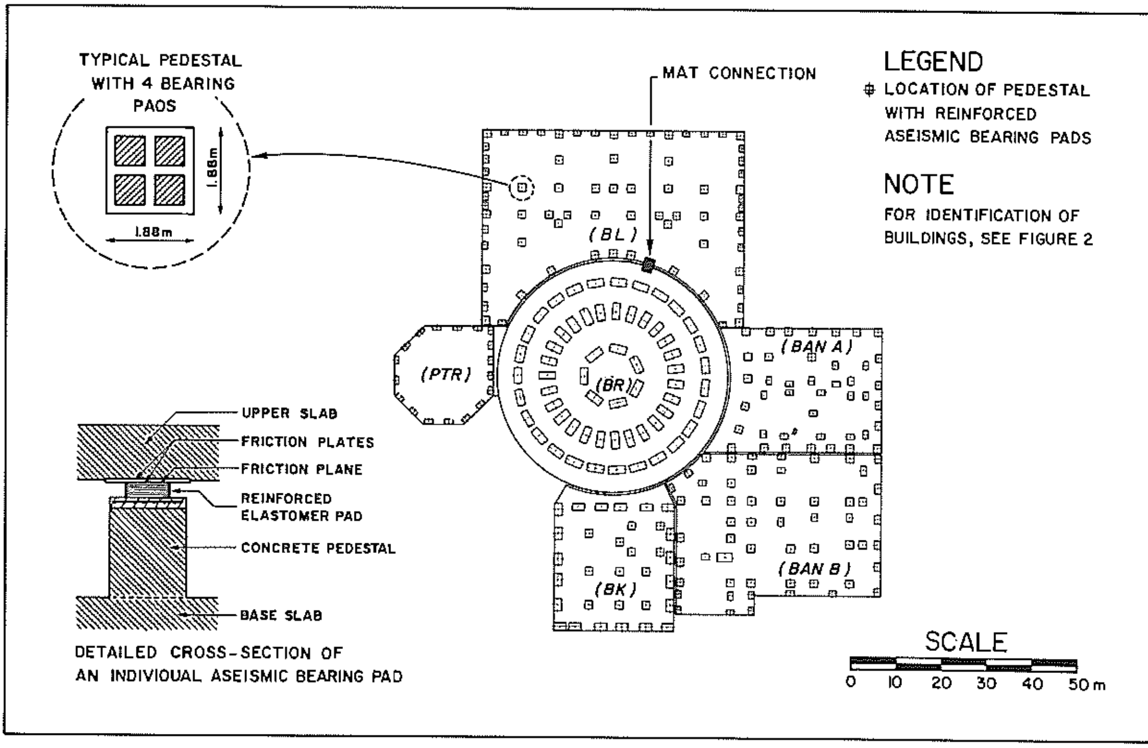

FIGURE 1 LAYOUT OF NUCLEAR ISLAND AND ASEISMIC BEARING PADS

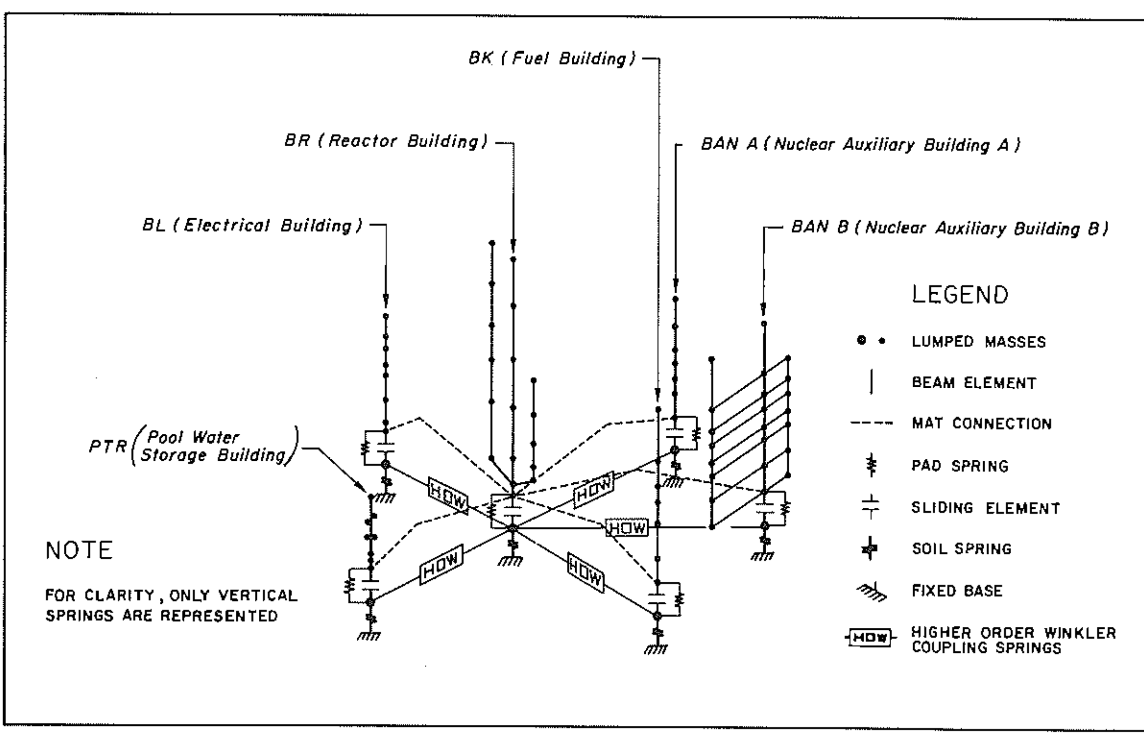

FIGURE 2 MODEL OF NUCLEAR ISLAND

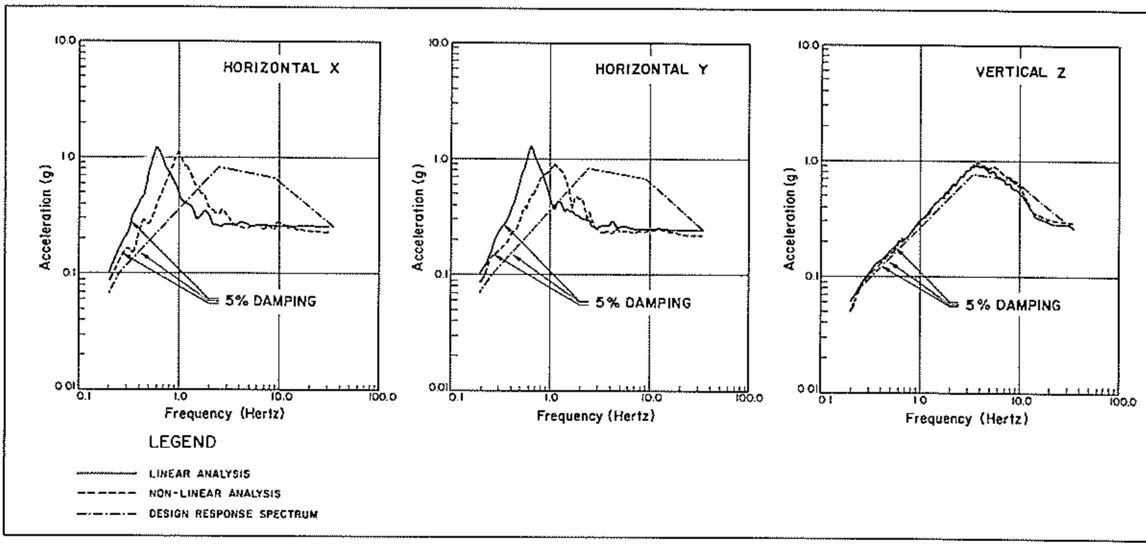

FIGURE 3 RESPONSE SPECTRA AT BASE OF REACTOR BUILDING

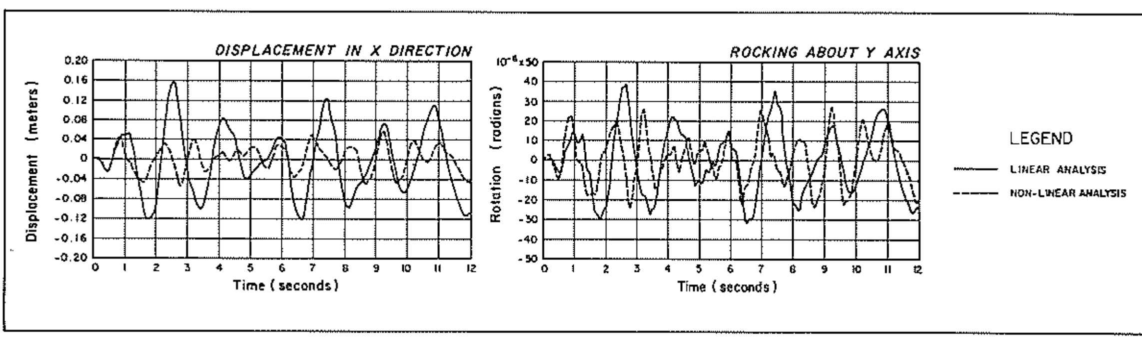

FIGURE 4 MOTIONS AT BASE OF REACTOR BUILDING

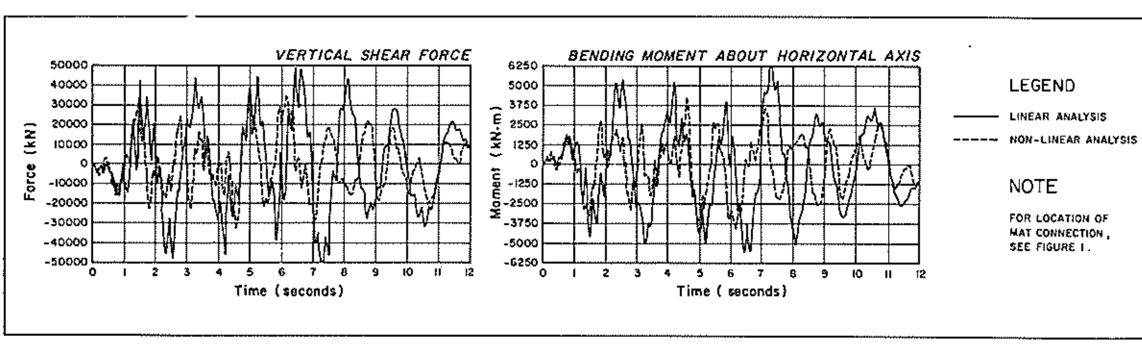

FIGURE 5 FORCES AND MOMENTS IN A TYPICAL MAT CONNECTION