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Response of a Base-Isolated Large Liquid Metal Reactor Plant to Seismic Loads

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INTRODUCTION

In recent years, base isolation has been applied to various civil structures such as bridges and buildings for the purpose of reducing its acceleration to below the level of ground accelerations during seismic events. The basic principal of base isolation is to introduce a soft layer of material between structure and foundation to allow a degree of flexibility in horizontal motions which could reduce the seismic accelerations during earthquakes. If base isolation is properly designed, it shifts the fundamental frequency of the structure away from the damaging frequency range of earthquakes. Thus, the seismic loads transmitted to the structure can be greatly reduced. This is particularly important in Liquid Metal Reactor (LMR) plants, because the components of primary system such as reactor vessel and piping loops are designed to be thin-walled structures and have little inherent seismic resistance. Thus, the use of base isolation offers a viable and effective approach that permits the reactor structures to better withstand the seismic loading.

This paper deals with the seismic response of a base isolated large-scale LMR plant. The analysis model was based on a preliminary nuclear island layout developed by EPRI during the concept development phase of the large-scale prototype breeder (LSPB) project. The nuclear island has a dimension of 184'-0" x 210'-6"; the reactor vessel has an ID of 62 ft and an overall length of 70 ft. Two soil conditions have been considered in the analysis. One is a hard-soil site having a shear wave velocity of 6000 ft/s, and the other is a soft-soil site having a shear wave velocity of 2000 ft/s. For comparison purposes, the response of a conventional plant (unisolated) was also analyzed.

MODEL OF LSPB PLANT

The LSPB plant consists of a single basemat which supports the reactor containment building (RCB), the steam generator building (SGB), the reactor service building (RSB), and the crane enclosure building (CEB). The mathematical model of the nuclear island is shown in Fig. 1. The buildings and reactor vessel are modeled with finite elements. They are represented by a number of beams and springs interconnected at their nodes and a number of masses lumped at floor levels, and are placed at the nodes as shown in Fig. 1. The reactor containment building, the steam generator building, and the reactor service building, are represented in beams 1-5 whereas the crane enclosure building is represented by beams 6-9 connecting nodes 8 and 302. The reactor vessel and its internals are represented by beams 101-117 together with springs K1, K2, and K4-10. Spring K3 represents the reactor vessel support skirt.

Under seismic excitation, the response of the plant is affected by the stiffness of the soil around it. Thus, the surrounding soil must also be properly included in the mathematical model. Here, we assume that the soil can be represented by a frequency independent spring and dashpot as shown in Fig. 1. For isolated plants, the nuclear island has two concrete foundation mats, and the isolators are placed between the two mats. The fundamental frequency of an isolated nuclear island ranges from 0.2 to 0.5 Hz. Here, we assume that the isolated plant has a fundamental frequency of 0.50 Hz.

SEISMIC INPUT

The seismic input used in the LSPB analyses is a synthetic earthquake acceleration time history which has a 19-s duration and 3801 data points digitized at 0.005 s intervals. The maximum peak acceleration of the time history has a zero period ground acceleration (ZPGA) of 0.3 g for sites with a low shear velocity of 2000 ft/s or less and a ZPGA of 0.2 g for sites with a high shear wave velocity of 6000 ft/s or greater.

DISCUSSION OF RESULTS

Four Cases have been studied. They are:

Case	Site Condition	Peak Ground Acc.	Base Isolation
1	Hard Soil, V_s=6000 ft/s	0.2 g	No
2	Hard Soil, V_s=6000 ft/s	0.2 g	Yes
3	Soft Soil, V_s=2000 ft/s	0.3 g	No
4	Soft Soil, V_s=2000 ft/s	0.3 g	Yes

The system frequencies are given in Table I.

Table I. System Frequencies, Hz

Case	Frequency, Hz				
	$\omega_{isolator}$	$\omega_{building}$	$\omega_{foundation\ mat}$	$\omega_{reactor\ vessel}$	ω_{core}
1	---	16.02	---	22.15	16.20
2	0.50	15.56	65.26	22.15	16.20
3	---	5.34	---	22.15	16.20
4	0.50	5.18	21.75	22.15	16.20

These frequencies were obtained from eigenvalue analysis. With this background information, we can now discuss the results of the analyses. The maximum peak accelerations at the top of the basemat (Node 1), reactor vessel support (Node 5), top of the reactor vessel (Node 102), core support structure (Node 107), top of the core barrel (Node 111), bottom of the reactor core (Node 123), and top of the core (Node 117) for cases 1-4 are shown in Table II. It can be seen in Table II that for hard soil sites, the base isolation with isolator frequency of .50 Hz can reduce the horizontal accelerations by a factor of two or more. However, for soft soil sites, the maximum peak accelerations at the top of the basemat and reactor vessel support are reduced very slightly, whereas at reactor components, the peak accelerations are greatly increased.

It should be pointed out that the increase in component accelerations is not due to the dynamic characteristics of the isolators which are unsuitable for soft soil sites. It is due to tuning and interaction of the frequency of the containment building (primary) with the frequencies of the reactor vessel and reactor core (secondary). It has been pointed out (Sachman & Kelly, 1978) that if the equipment frequency (secondary) is tuned to a structure frequency (primary), there exist two closely spaced frequencies on either side of the tuning frequency around which a band of high amplification appears. A typical result of a tuned equipment - structure system is shown in Fig. 2 in which the equipment was tuned to the third structure frequency, and γ is the mass ratio of the equipment to structure. It can be seen from the Fourier frequency spectrum curve shown in Fig. 3 that tuning and interaction of component and structure frequencies occurred in the present analysis. The two high-amplification regions around the tuned frequency are clearly shown.

As mentioned earlier, the reactor core has a frequency of 16.20 Hz, and the reactor vessel has a frequency of 22.15 Hz. The two frequencies introduced by the use of isolators on a hard soil site are 0.50 Hz of isolator frequency and 65.26 Hz of basemat frequency. They are not in tune with the component frequencies. However, on a soft soil site, the two new frequencies introduced by base isolation are 0.50 Hz of isolator frequency and 21.75 Hz of basemat frequency. The basemat frequency is in tune with the reactor vessel and reactor core. Thus, due to tuning and interaction, the responses of the components, especially the reactor vessel and reactor core, are greatly amplified. It is this amplification which makes the results of component responses unacceptable.

To prove that tuning and interaction of frequencies between the components and lower basemat are the main reason for the occurring of amplifications, we use a detuned system in which the reactor vessel frequency is reduced to about 6.5 Hz by using a softer spring at the reactor vessel support. Actually, detuning of the system frequencies can be achieved in several ways. For example, one can detune the lower basemat frequency. Since the frequency of the lower basemat is related to the surrounding soil, detuning its frequency would involve the change of the mass of the basemat and the spring constant of the soil. The change of the soil spring constant is considered to be undesirable because we want the LSPB base isolation design to be able to use under all soil conditions. Thus, detuning is accomplished through the use of a softer spring at the reactor vessel support. The spring constant, K3, of the reactor vessel support in the detuned system has a value of 0.112 E7 kips/ft. Therefore, the reactor vessel has a frequency of 6.5 Hz which is not in tune with the lower basemat frequency. The maximum peak accelerations on reactor components of the detuned system are given in Table 1. It can be seen that they are also reduced by a factor of two or more.

CONCLUSIONS

It has been demonstrated that seismic base isolation is a useful device for reducing the structures and components accelerations to below the level of ground accelerations. The results of the LSPB analyses show that the base isolation can reduce horizontal accelerations by a factor of two or more.

The basic principal of base isolation is to shift the fundamental frequencies of the structures and components away from the damaging frequency range of earthquakes, so that seismic loads transmitted to the structures and components would not be amplified. Since base isolators act as a soft layer of material separating the structure with the surrounding soil and allowing a degree of flexibility in horizontal motions, it also introduces two new frequencies in the isolated system. One is the fundamental frequency of the isolators which is usually in the range of 0.20-0.50 Hz and has no effects on structural response. The other is the frequency of the lower basemat which is in the range of 20-60 Hz depending on the soil stiffness and will affect the structural response. If the frequency of the lower basemat is in-tune with one of the component frequencies, tuning and interaction of frequency can occur in the isolated system and the seismic response can be greatly amplified. This has been demonstrated by the results of the in-tuned and detuned analysis. Thus, one should be very careful in the application of base isolation to reactor plant that the frequencies of the components should be detuned from the lower basemat frequency.

REFERENCE

Sachman, J. L. and Kelly, J. M. (1978). Rational Design Methods for Light Equipment in Structures Subject to Ground Motion. VCB/EER-78/19.

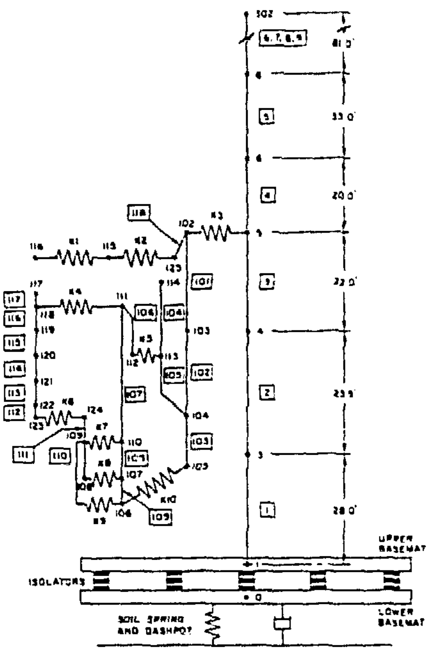

Fig. 1. Mathematical Model of LSPB Plant

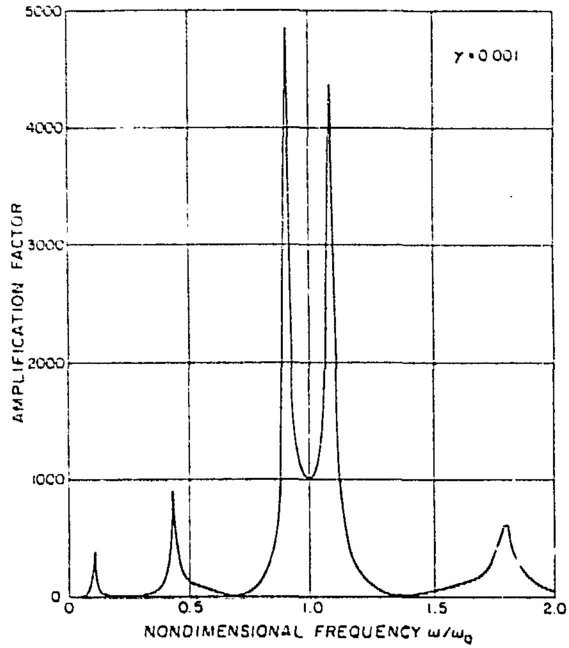

Fig. 2. Amplification Factor for Equipment Acceleration as a Function of Frequency -- Equipment Tuned to Third Structure Frequency.

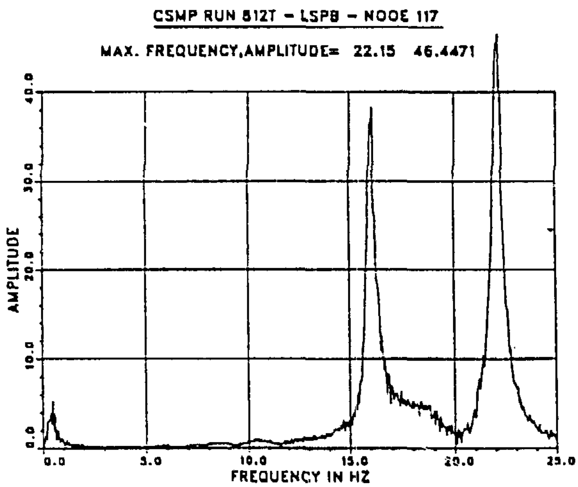

Fig. 3. Acceleration Time History and Frequency Spectrum, Node 117, Case 4, In-tune.