Comparative studies of isolation systems applied to a compact LMR reactor module*

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ABSTRACT

We investigated the responses to horizontal input ground motions of a compact LMR reactor module incorporated with three different isolation systems: a steel plate reinforced elastomer pad design without friction plates (called the linear system); the same pad with friction plates (called the bilinear system); and the Alexisismon design which uses rubber springs and teflon pot bearings to carry horizontal and vertical loads, respectively. Essential parameters characterizing the isolation systems, such as isolation frequency, are chosen consistent with those available in the open literature for these systems.

All three isolation systems significantly reduce the horizontal shear force transmitted to the reactor system. The bilinear system, due to the friction plates, limits the maximum shear force transmitted to a preset value. The Alexisismon design, which may use a very soft spring and, therefore, exhibits a much lower isolation frequency than the other two designs, gives the most reduction in shear force.

Among these three isolation systems, the linear system yields the smallest maximum acceleration for the isolated reactor. The Alexisismon design not only produced the highest maximum acceleration, but also showed amplification in acceleration. Acceleration amplification is also observed in the bilinear system for some of the ground motions considered. It appears at this time that this acceleration amplification is caused by the nonlinearity of the isolation systems. Further study is definitely warranted.

1 INTRODUCTION

Because of current requirements on safety and reliability, nuclear power plants are to be designed against seismic events even for the areas once thought seismically inactive. The conventional approach to a seismic design is to provide sufficient strength and ductility in the structures and components to resist the earthquake forces. This may result in heavy-walled vessels, pipings, and structural components.

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An alternate approach is to use a seismic isolation scheme which reduces the seismic forces transmitted to the isolated structure by shifting the important natural frequencies of the structure away from the more damaging frequency range of the strong motion of earthquakes. The shifting of structural frequencies is usually accomplished by incorporating a flexible support to the structure, such that the isolated structure has lower natural frequencies and thus avoids the damaging high-frequency power range of earthquakes.

For reactors designed for low pressure but severe thermal transients, thin-walled components are generally preferred. It is, therefore, not an easy task to design them against strong earthquakes and severe thermal loadings simultaneously. Seismic isolation, therefore, becomes especially attractive in these reactors.

With seismic isolation, the seismic loading transmitted to the structure is reduced. Reliability and design margins of the structure in resisting earthquake loads are also increased. These, in turn, reduce the sensitivity of the plant's response to local soil environment; therefore, the effects of uncertainty involving soil properties are much reduced.

2 DESCRIPTION AND MODELING OF THE REACTOR

The reactor module of a compact liquid metal reactor (LMR), shown in Fig. 1, has a diameter and height of approximately 6m (20 ft) and 18 m (60 ft), respectively. Not included in this figure are the reactor vessel auxiliary cooling system (RVACS) and the head access area (HAA). Note that the bulk of the mass of the reactor module is concentrated at discrete locations such as the reactor closure or deck, and the core and shielding, a spring-mass system is considered adequate for the present investigation. Figure 2 is the analysis model which is intentionally made simple in order to efficiently evaluate linear and nonlinear systems under various seismic loadings as well as different soil conditions.

Before this simple spring-mass model (Fig. 2) was chosen as the basic model in this study, other spring-mass models were also examined. It is observed that these models yield almost the same results. Furthermore, it has been pointed out in [1] that there is little difference between the results from a simple model and from a more detailed model for a reactor with seismic isolation. The model of Fig. 2 is thus used in most of the seismic isolation studies for the reactor module under horizontal seismic loadings.

In the analysis, the reactor module is attached either to the ground when there is no isolation, or to one of the isolation systems described in Section 3 when there is isolation. In the unisolated case, the structure is assumed built upon either soft soil with a shear velocity of 600 m/s (2,000 f/s), or upon hard soil with a shear velocity of 1800 m/s (6,000 f/s).

Springs and dampers have been used to simulate different isolation systems. In these simulations, the springs can be linear or bilinear. The bilinear spring considered here behaves linearly until a maximum spring force has been reached. After that, the spring force remains constant during loading but behaves linearly during unloading. The dampers are either of linear viscous or of Coulomb friction type. Other than that inherent in the material of the isolation system, no additional damping has been included in the modeling. Free surface sloshing of the reactor coolant is not examined in this investigation.

3 ISOLATION SYSTEMS AND TIME HISTORIES

Three isolation designs have been studied: They are: (1) reinforced elastomer design without friction plates [1], or linear system, (2) reinforced elastomer design with friction plates [1], or bilinear system, and (3) Alexisismon design [2], which uses rubber springs and pot bearings to carry horizontal and vertical loads, respectively.

In the linear system, isolation is provided by the reinforced elastomer, i.e., elastomer embedded in steel plates. During an earthquake, the elastomer, or seismic isolator, acts as a soft horizontal spring and responds linearly. The isolated structure will vibrate and return to its initial position after the earthquake. There will be no permanent displacement as long as strains remain in the elastic range.

In addition to the reinforced elastomer, as in the linear system, the bilinear system uses friction plates to limit the maximum horizontal force transmitted to the structure. During earthquakes, the elastomer deforms linearly with force, as in the linear system. When the earthquake becomes stronger and the force of the elastomer reaches or exceeds the limiting or maximum force, slipping between the plates occurs. As a result of this slipping, horizontal displacement of the elastomer is limited, thus avoiding the potential buckling of the elastomer or seismic isolator. Note there is no limitation on the horizontal displacement of the structure except it design performance limit. For low-intensity earthquakes, this design behaves just as the linear system. For earthquakes of higher intensity, relative displacement (slipping) between the friction plates occurs. The structure could exhibit some permanent displacement after an earthquake (usually just a few inches).

In the Alexisismon design, horizontal isolation is mainly provided by the rubber spring or bearing which does not support any vertical load. Vertical load is supported entirely by the pot bearing. There will be some horizontal friction force when the pot bearing has sliding motion. Because of this friction, the isolated structure may exhibit some small amount of permanent displacement after an earthquake.

In the limiting case when the friction force is zero, the Alexisismon design reduces to the linear system. However, in the Alexisismon system, the isolation frequency (i.e., the lowest natural frequency of the isolated structural system) can be very low compared with other designs. This is because the rubber bearing which provides the horizontal stiffness of the isolation system does not carry any vertical load, thus eliminating the concerns for buckling of the rubber bearing from large relative horizontal displacement. This is not true for the linear system, where the vertical weight of the structure is carried by the elastomer, which may buckle when the relative horizontal displacement becomes excessive. Thus, the attainable isolation frequencies for the linear system may be different from those of the Alexisismon designs. Hence, different isolation frequencies are used in analyzing the reactor module with the different isolation systems.

Isolation frequency, which relates the total mass of the system being isolated and the stiffness of the isolator, is generally very low to be away from the damaging frequency range of strong earthquake motions. The isolation frequencies used in this analysis are 0.5, 0.67, and 0.17 Hz, respectively, for the linear system, the bilinear system, and the Alexisismon design. The maximum frictional force between the friction plates for the bilinear system is 20% of the total weight of the structure and 5% for the pot bearing in the Alexisismon design. These parameters are consistent with those used elsewhere.

To obtain some measure of the effectiveness of the isolation systems, responses of unisolated systems under the same earthquake loadings are also obtained. The unisolated systems are modeled by assuming that the structure is built upon a soft soil site (with soil shear velocity of 600 m/s) or a hard soil site (with soil shear velocity of 1800 m/s), respectively. The necessary equivalent linear spring and damper corresponding to an infinite soil media are obtained from known relations [3].

A total of eight well characterized and representative acceleration time-histories have been used in this investigation. These include one synthetic time-history whose spectrum envelopes that suggested in USNRC Guide 1.60, the well known El Centro record, and the 1935 record at Helena, Montana which is close to a potential plant site. The other five time-histories based on their strong motion duration, local magnitude, and frequency content, have been included in a study on the engineering characterization of earthquakes ground motion for nuclear power plate design [4].

4 SUMMARY OF RESULTS

When an isolation system described previously is incorporated into the reactor module where the site soil shear velocity is either 600 m/s or 1800 m/s, results show an insignificant effect of the site soil property on the responses. Such results have also been observed in [1]. This is expected, since the stiffness of an isolation system with an isolation frequency of 0.67 Hz or less is much softer than the soil stiffness considered here. Accordingly, such low-frequency seismic isolator can be modeled as fixed at the bottom, or neglecting the soil stiffness when the soil shear velocity is equal to or higher than 600 m/s.

Table I presents the shear force transmitted to the reactor module for different isolated and unisolated environments. It is evident that when seismic isolators are present, there is a significant reduction in the shear force transmitted. The bilinear system, due to the use of friction plates, limits the maximum shear force transmitted to the preset value of 20% of the total weight of the system. The Alexisismon isolator, which has a much lower isolator frequency or very soft spring, shows little increase in the shear force transmitted even when the maximum ground acceleration is increased from 0.3 g to 1.2 g.

Table I also indicates that when the input maximum acceleration (or ZPA) is scaled to higher values, responses of the linear system will increase proportionally. The bilinear system, by its design, limits the force transmitted to a preset value (20% of the total system weight in this study) under any seismic input. The increment in force transmitted with respect to ZPA is smaller in the Alexisismon design than the other two designs. Maximum acceleration of the reactor system generally increases with the input ZPA except in the two instances marked in Table I, which could be the result of the nonlinearity of the isolation system.

In Table II, a summary of responses for the reactor module isolated with different isolation systems under different acceleration time-histories is presented. Results indicate that all three isolation designs reduce the shear force transmitted. Among the three isolation designs, the Alexisismon design generally gives the most reduction in shear force. The bilinear system, with the coefficient of friction used in this study, limits such shear force to 20% of the reactor system's total weight.

The maximum acceleration of the entire reactor system given in Table II occurs mostly at the core location. Of the three isolation designs investigated, the linear system yields the smallest maximum acceleration. The Alexisismon design not only produced the highest maximum acceleration, but also has the maximum acceleration of the entire system higher than the maximum input acceleration of 0.3 g, i.e., there appears to be acceleration amplification. Such amplification could be the result of the nonlinearity introduced by the Coulomb friction force of the system. When the Coulomb friction force is kept unchanged while the maximum input acceleration is scaled to higher values, such amplification is reduced or there is no amplification (Table I). Alternatively, amplification can be reduced or eliminated by reducing the Coulommb friction force (or friction coefficient) when there is no change in the input acceleration. Acceleration amplification is also observed when the bilinear system is subjected to the time-histories obtained from the synthetic time-history and that recorded at Hollywood Storage P. E. lot.

Table II also summarizes the peak relative displacement for each of the three isolation designs. It is of interest to note that the bilinear system, which has the highest isolation frequency in this study, does not always yield the smallest relative displacement among these three isolation designs.

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Table 1. Variations of Responses with ZPA of an Isolated Reactor Module

Time Histories	ZPA (g)	Maximum Shear Transmitted (% total wt) With Isolation Linear (.5 Hz)	Bilin. (.67. Hz)	Alexis. (.17 Hz)	Without Isolation site shear vel (m/s) 600	1800	Peak Acceleration (g) Linear (.5 Hz)	Bilin. (.67 Hz)	Alexis (.17 Hz)
Synthetic	0.3	22.6	20	7.4	83	112	.26	.32	.36
	0.6	45.2	20	9.7	--	--	.51	.32*	.48
	1.2	90.4	20	11.0	--	--	1.02	.52	.57
El Centro	0.3	13.2	20	5.8	66	76	.15	.25	.41
	0.6	26.4	20	7.4	--	--	.30	.35	.60
	1.2	52.8	20	12	--	--	.60	.50	.76
Helena Montana	0.3	3.4	6.0	5.3	64	92	.05	.10	.51
	0.6	6.8	14.0	5.4	--	--	.11	.20	.52
	1.2	13.6	20	6.0	--	--	.22	.34	.48*

*Peak acceleration did not increase with input ZPA

Table 2. Peak Acceleration and Relative Displacement of an Isolated Reactor Module Under Different Time-Histories

Time Histories*	Peak Acceleration (g)			Peak Rel. Displ. (cm)		
	Linear (.5 Hz)	Bilin. (.67 Hz)	Alexis. (.17 Hz)	Linear (.5 Hz)	Bilin. (.67 Hz)	Alexis. (.17 Hz)
Synthetic	.26	.32	.36	19.2	22.3	21.3
El Centro	.15	.25	.41	6.4	13.1	13.1
Helena, Montana	.05	.10	.51	1.5	3.7	4.0
Taft, California	.15	.26	.30	5.5	14.0	15.5
Olympia, Washington	.12	.21	.35	7.0	10.7	10.4
Cholame, California	.25	.28	.35	17.1	22.9	22.3
Pacoima Dam	.13	.28	.44	3.1	12.3	13.4
Hollywood	.16	.32	.37	8.2	11.3	18.0

*Maximum acceleration was scaled to 0.3 g

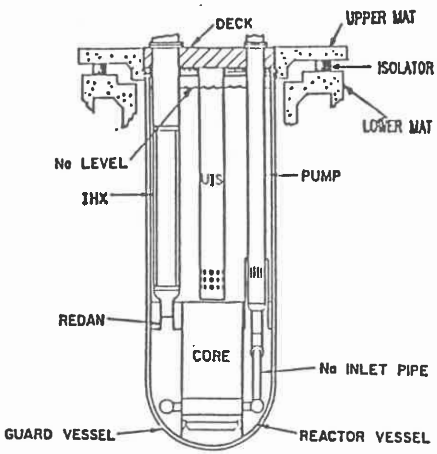

Fig. 1. Schematic of a Reactor Module with Seismic Isolation

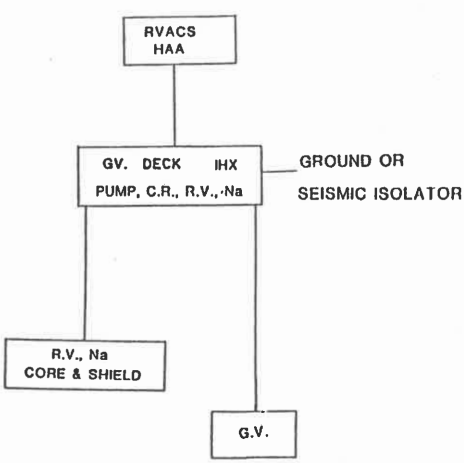

Fig. 2. Analysis Model for an Isolated Reactor Module