Response of Seismic Isolated Structures during Extreme Events

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1 INTRODUCTION

In recent years major research programs have been initiated in several countries to examine the feasibility of using seismic isolation in future nuclear facilities. The findings of these programs to date have been very positive and several benefits of seismic isolation have been identified (Tajirian et al. 1990; Shiojiri and Ishida 1990). It has also been recognized that prior to licensing of this technology some technical issues which are not encountered in existing non-isolated plants would require better understanding. Two Critical issues, especially in areas of high seismicity, are how much margin beyond the Safe Shutdown Earthquake (SSE) is required in the design of the isolators and how to evaluate the capacity of the isolated structure for beyond design basis earthquakes (BDBE) with very long return periods (>10,000 years). Probabilistic techniques have been developed to assess the risk of damage to fixed-base plants and components which use the maximum ground acceleration as the only parameter for including the earthquake contribution. These methods are not directly applicable to isolated structures which normally have predominant periods between 1 to 2 seconds because they do not accurately portray the effects of the long period components of ground motion. An isolated structure and its contents will not respond to inputs with high frequency accelerations as a non-isolated structure would.

In this paper the differences between the long period (T>2 sec) and high frequency (f>2 Hz) components of earthquakes are reviewed. Synthetic earthquake time histories are developed for a generic site in California close to major faults for two earthquake levels, SSE and BDBE. Dynamic analyses are performed to compute the response of the isolated PRISM (Power Reactor Innovative Small Module) Advanced Liquid Metal Reactor (ALMR) (Berglund et al. 1990). PRISM, which weighs about 4000 tons, is supported on twenty steel-laminated high damping elastomeric seismic isolation bearings (SIB). The module is isolated in the horizontal direction and the predominant isolation frequency is 0.75 Hz. The seismic design basis for PRISM is a SSE level with a maximum horizontal and vertical acceleration of 0.3g anchored to a design earthquake that envelopes the U.S. NRC Regulatory Guide 1.60 spectra. The reference bearing design developed for 0.3g has a diameter of 132 cm and a total height of 58 cm, consisting of 30 layers of rubber 1.3 cm thick and 29 steel plates 0.3 cm thick (Tajirian et al. 1990).

2 ESTIMATION OF LONG PERIOD GROUND MOTIONS

There is a fundamental difference between high frequency and long period ground motions. High frequency motions are affected by complexities in the seismic source (e.g. variability in the rupture velocity, amount of slip, and rate of slip along the fault) and in the geologic structure (scattering). In other words, the high frequency motions are strongly affected by spatial and temporal derivatives of the seismic source. Since such derivatives can vary widely, high frequency motions appear stochastic and can reach very large values (>2g) in extreme cases.

In contrast, long period motions are primarily affected by the average values of the seismic source (e.g. average rupture velocity, fault area, rate of slip, and focal mechanism). In this sense, the long period motions are deterministic; the long period motion can be predicted reasonably well if the overall seismic source parameter values are known (Spudich and Archuleta 1987). By definition, the moment magnitude of an earthquake is proportional to the log of the average displacement on the fault. Since a value parameter is more stable than its derivative, the long period motions are more stable than the high frequency motions. For example, studies of spatial coherency have shown that high frequency motions can vary significantly over short distances (10-100m) whereas long period motions are nearly identical over short distances (Abrahamson et al. 1990).

This difference between high frequency and long period motion has important implications for extreme events. High frequency ground motion estimates are typically treated probabilistically. The shape of the tail of the assumed probability distribution becomes very important in calculating low probability ground motions. To determine the shape of the tail of the distribution requires understanding of the underlying causes of the variability. As noted above, high frequency motions appear stochastic due to random variations in the source parameters and geology structure; they appear to follow a log-normal distribution up to at least 3σ (standard deviations)(Abrahamson 1988). Therefore, for a given earthquake magnitude and ray path (regional geology and source distance), variability of long period motion is primarily due to variations in average seismic source parameters including rupture velocity (directivity), focal mechanism, rise-time, and stress-drop. Since the long period motion depends on average values of source parameters which have physical limits, the tail of the distribution is truncated lower than for high frequency motions. This difference is shown schematically in Figure 2.

For a highly active region (e.g. California) in which the maximum magnitude earthquake has a return period of only several hundred years, the long period motion for a 1000 year event would have reached its limit and therefore an earthquake with a longer return period (e.g. 100,000) cannot be larger. This is in contrast to the high frequency components which may be significantly higher. A more detailed discussion is given by Abrahamson (1990).

3 DESIGN EARTHQUAKES

In this study, the ground motions are generated by combining a modified Brune Fourier amplitude spectrum (Boore 1983) with an empirical phase spectrum (Silva and Lee 1987). An equivalent point source model is used in which the source distance is adjusted to account for the extended fault effect. The main source parameters for this model are the magnitude, stress-drop, and focal mechanism. Other source parameters including rupture velocity, and rise-time are not used explicitly in the model. Stochastic variations in the Fourier amplitude spectrum are included so that multiple sets of ground motions can be computed.

For the SSE, a moment magnitude 8.0 earthquake is used, similar to the 1857 and 1906 California earthquakes. An equivalent point source distance of 12 km lead to a horizontal peak ground acceleration (PGA) of about 0.75g. The acceleration time histories are shown in Figure 3 and their acceleration response spectra in Figure 4. For the BDBE, the moment magnitude was increased to 8.5, representing rupture of the entire San Andreas fault, which is very conservative but nevertheless represents an upper bound. An equivalent point source distance of 9 km lead to a horizontal PGA of about 2g. The acceleration time histories are shown in Figure 5 and their spectra in Figure 6. The RG1.60 spectra are also shown for comparison purposes.

4 SEISMIC ANALYSIS

The seismic response of the isolated reactor facility was computed using time history analysis. The reactor was modelled as an assemblage of beams and lumped masses. The isolators were represented by springs whose stiffnesses were selected to yield a horizontal frequency of isolation of 0.75 Hz and a vertical frequency of 24 Hz. A damping factor of 10 percent was assumed for the isolators. Two site conditions were considered, a rock site with a constant shear wave velocity of 1830 m/s, and a soil site with a shear wave velocity of 304 m/s.

The response of the isolated reactor module was computed using the 0.75g SSE and BDBE level synthetic time histories described above, as well as time histories which envelope the NRC RG1.60 spectra scaled to 0.75g. The maximum accelerations and displacements just above the isolators, at the reactor vessel support, and at the core support are summarized in Tables 1 and 2. As expected the isolated structure moves as a rigid structure on top of the isolators with very small amplification in horizontal accelerations and all the displacements are confined to the isolators. The soil stiffness does not have an effect on the response in the horizontal direction, while in the non-isolated vertical direction the accelerations are higher for the soft soil case. The maximum SSE horizontal accelerations are similar for the two time history sets used, and a 9 percent reduction of accelerations is observed relative to the peak ground acceleration. For the BDBE there is a 36 percent reduction mainly because the long period components of the input earthquake do not scale at the same rate as the high frequency components.

The maximum horizontal displacement for the SSE in one direction across the SIBs is 28 cm for the RG1.60 input, 31 cm for the synthetic input, and for the BDBE level the displacement is about 54 cm. By scaling the SSE results to the 2g level one would get 75 cm for the RG 1.60 input. The closeness of the accelerations and displacements at the SSE level for the two earthquakes used indicates that the RG1.60 can appropriately represent the SSE level, however the large discrepancy at the BDBE level confirms that it would be too conservative to scale the RG1.60 spectra across the entire frequency range using the peak acceleration, see Figure 6.

5 CAPACITY OF THE SEISMIC ISOLATION BEARINGS

One of the objectives of this study is to evaluate the design of the SIBs for different earthquake levels, and to determine whether they are capable of accommodating displacements resulting from very large earthquakes. Extensive tests were performed on the reference SIB described above at the University of California Earthquake Engineering Research Center (EERC), and at the Energy Technology Engineering Center (ETEC) (Tajirian et al. 1990; Gluekler et al. 1989). The tests were performed on half-scale and quarter-scale bearings and demonstrated that some of the bearings were capable of accommodating 300 percent shear strain (110 cm in full-scale) indicating that the bearings have substantial margins for the 0.3g level earthquake, and are capable of accommodating even the displacements resulting from the BDBE event. Tests were later performed on other small-scale SIBs (Kelly 1991), which showed that bearings can be designed which are capable of accommodating 500 percent shear strain, and that the displacements are limited by the bearing diameter rather than shear strains in the rubber. Similar results have been obtained by several investigators in Japan including Fujita 1989 and Iizuka et al.

1990. These results indicate that the existing technology for manufacturing steel-laminated rubber bearings has made big advancements in recent years and it is possible to manufacture large diameter bearings which can accommodate displacements up to 150 cm or more.

It should be noted that the analysis performed in this study was based on simplified linear models. However, tests have shown that bolted bearings have very favorable non-linear stiffness characteristics whereby the bearing horizontal stiffness increases progressively above 200 percent shear strain and maintains this stiffness up to failure, thus providing an inherent restraint mechanism that will limit displacements, and reduce the potential for resonance at the isolation frequency even if the system was totally undamped. Non-linear analyses will be performed on the PRISM plant to quantify these effects in future margin evaluations.

Finally the effects of net tension on the bearings due to large vertical inputs or rocking will tend to reduce the failure strain levels. Although in PRISM, rocking effects are minimized because the center of mass of the isolated plant is close to the elevation of the isolation, this effect may be pronounced in plants where the overturning effects are higher.

Table 1. Maximum Response Accelerations (g)

Location	Axis	SSE-RG1.60(0.75g)		SSE-Synth.(0.75g)		BDBE-Synth.(2.0g)	
		Soil	Rock	Soil	Rock	Soil	Rock
Top of Isolators	Horiz.-1	0.68	0.68	0.66	0.67	1.27	1.27
	Horiz.-2	0.68	0.68	0.75	0.75	1.27	1.27
	Vertical	1.40	0.80	1.28	1.06	1.51	1.35
Reactor Vessel Support	Horiz.-1	0.68	0.68	0.66	0.67	1.28	1.28
	Horiz.-2	0.68	0.68	0.75	0.75	1.28	1.28
	Vertical	1.43	0.83	1.30	1.06	1.53	1.37
Core Support	Horiz.-1	0.71	0.72	0.73	0.71	1.37	1.32
	Horiz.-2	0.68	0.68	0.78	0.79	1.33	1.32
	Vertical	1.61	2.05	1.58	2.03	2.25	3.26

Table 2. Maximum Response Displacements (cm)

Location	Axis	SSE-RG1.60(0.75g)		SSE-Synth.(0.75g)		BDBE-Synth.(2.0g)	
		Soil	Rock	Soil	Rock	Soil	Rock
Top of Isolators	Horiz.-1	27.9	28.0	29.3	29.1	53.5	53.6
	Horiz.-2	27.9	27.8	31.1	31.2	53.6	53.6
Reactor Vessel	Horiz.-1	28.0	28.1	29.3	29.2	53.6	53.6
	Horiz.-2	27.9	27.8	31.2	31.3	53.6	53.6
Core Support	Horiz.-1	29.1	29.2	30.5	30.4	55.8	55.8
	Horiz.-2	28.9	28.8	32.3	32.4	55.7	55.8

6 CONCLUSIONS

This paper has shown that it is important to recognize the fundamental differences between high frequency and long period ground motions in the evaluation of the response of isolated structures to extreme events. The large peak ground accelerations normally computed in probabilistic analyses when considering extreme earthquakes do not govern the dynamic response of isolated structures. Rather the long period components which have not played a role in the design of non-isolated structures should be properly addressed. Recent seismological findings have shown that modelling techniques are less error prone in estimating the long period components and that the displacements during an extreme event are bounded by the physical characteristics of the seismic source. Additionally, preliminary calculations have shown that high quality steel-laminated elastomeric bearings can be manufactured which can accommodate the resulting displacements from a maximum hypothetical earthquake occurring on the San Andreas earthquake in California, assuming a moment magnitude of 8.5, representing rupture along the entire length.

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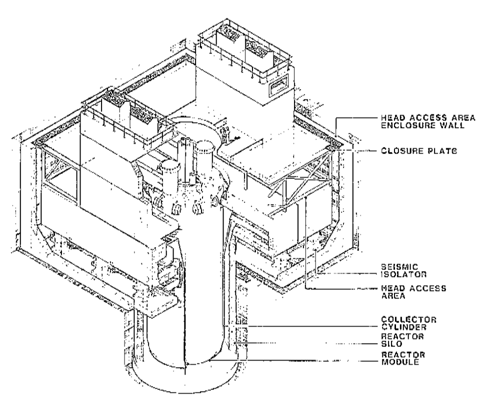

Fig. 1 PRISM ALMR Reference Design

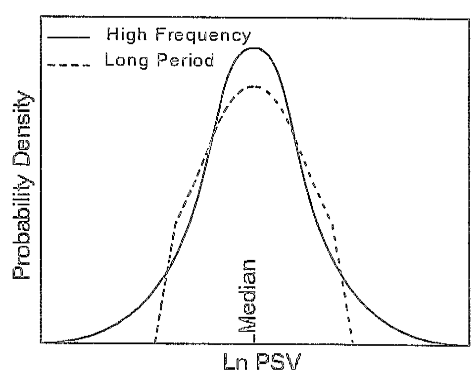

Fig. 2 Probability Distribution Curve

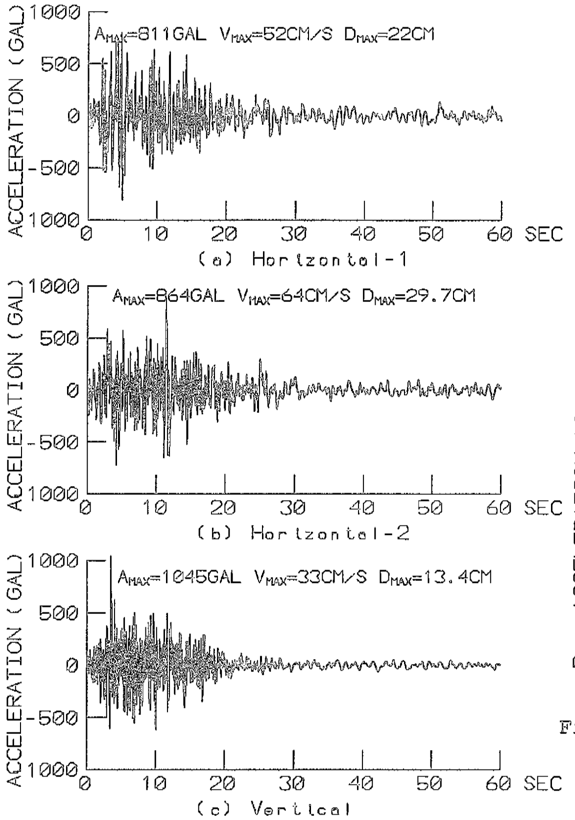

Fig. 3 SSE Level Synthetic
Time Histories

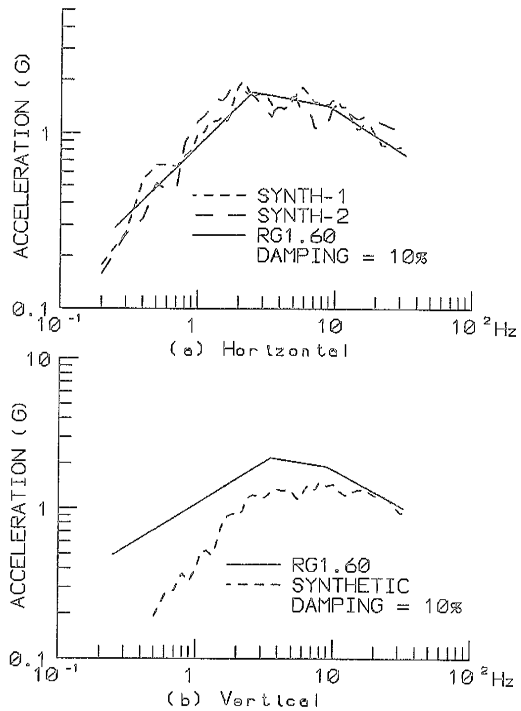

Fig. 4 SSE Level Response Spectra

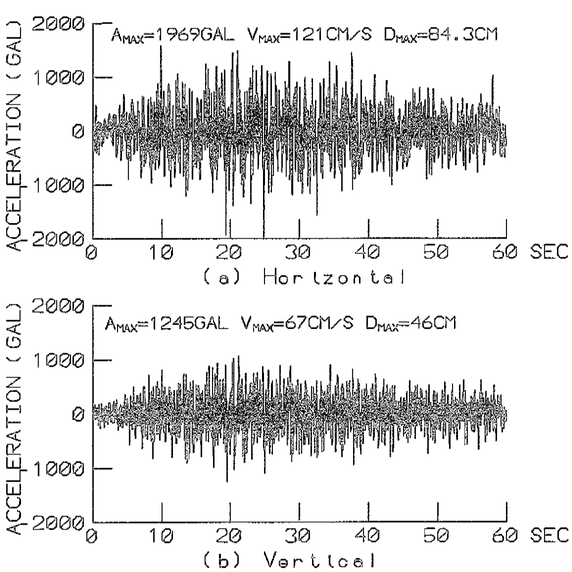

Fig.5 BDBE Level Time Histories

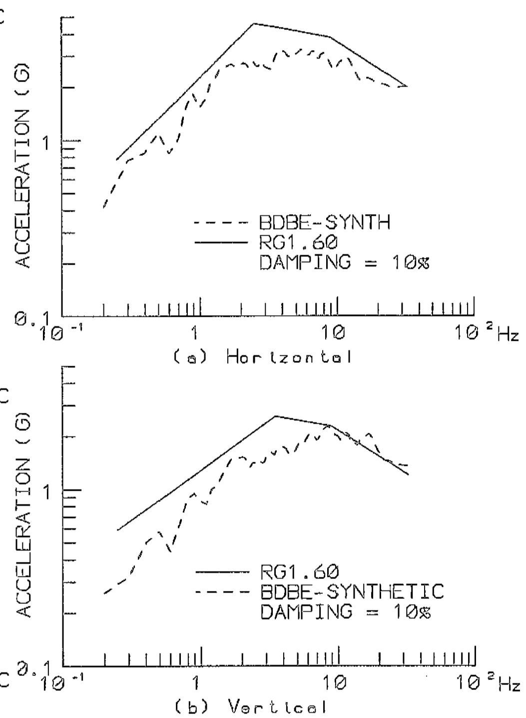

Fig. 6 BDBE Level Response Spectra