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Response of Seismic-Isolated Structures under Long-Period Motions

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1 INTRODUCTION

In the last decade, considerable progress has been made on seismic isolation to reduce seismic response of structures. At the present time, there are many seismic isolated structures, including both new and renovated structures. Extensive research on the application of seismic isolation on nuclear power facilities is also being conducted [1,2]. This paper presents an analysis of the response of seismic-isolated nuclear structures under long-period motions. The information presented here is useful to the future design of seismic-isolated structures.

2 RESPONSE OF BASE-ISOLATED STRUCTURES UNDER LONG-PERIOD MOTIONS

A preliminary study is carried out at ANL to investigate the effects of the long-period motions on seismic-isolated structures. In the study, a tentative long-period design response spectrum is used to represent the long period motions. Figure 1 shows the tentative long-period design response spectrum [3] and the conventional design spectrum anchored at 0.2 g ground ZPA. Three synthetic acceleration records are generated from the long-period spectrum. For comparison purposes, a synthetic record generated from the conventional spectrum is also used in the analysis. Figure 2 shows the generated acceleration history from the conventional and the long-period spectrum. Figures 3 and 4 show the acceleration spectrum and displacement spectrum of the two histories shown in Fig. 2.

Nonlinear time history analysis is carried out for a seismic-isolated nuclear building designed to have a fundamental frequency of 0.75 HZ subjected to these base motions using the model shown in Fig. 5. The ANL-developed SISEC (Seismic Isolation System Evaluation Code) computer code is used in the numerical calculation. The steel-laminated rubber bearings (see Fig. 6) between the upper and lower mat are simulated by the elasto-plastic springs which have bi-linear force-displacement relationship as shown in Fig. 7. In order to study the effects of isolator damping, three damping ratios are assumed for the bearings, 3%, 7%

and 15% (15% for high damping rubber material) of critical viscous damping. Structural damping is assumed to be 3% and 7%. For simplicity, the soil medium is represented by linear soil springs and dampers. Note that both rubber bearings and soil medium are strain-dependent nonlinear materials. Future analysis should consider the nonlinear soil effects. The material properties of soil and rubber are briefly described in next section.

Table 1 shows the maximum calculated accelerations at the top of the reactor buildings for the three damping cases (see Table 1) under various base motions. Table 2 summarizes the calculated maximum relative displacement between the upper and lower mat. For comparison purposes, the 3% and 7% damping spectral displacements and spectral accelerations at frequency of 0.75 HZ are also shown in Tables 1 and 2. The results indicate that the maximum acceleration in the structure increases from about 0.13 g for the case of conventional-type ground motion to about 0.25 g for the long-period wave cases. The structural acceleration is decreased from 0.25 g to 0.23 g when the isolator viscous damping is increased from 7% to 15%. Variation of isolator damping has little effect on the structural acceleration response. The calculated structural accelerations are not sensitive to the long-period motions. On the other hand, the calculated relative displacement between the upper and lower mats are very sensitive to the three long-period motions used in the analyses. The calculated relative displacement between the upper and lower mats ranges from 5.1 to 7.9 inches for 7% isolator damping and from 3.0 to 5.6 inches for 15% isolator damping. It indicates that viscous damping of bearings can effectively reduce the relative displacement between upper and lower mats. Figure 8 shows the calculated relative displacement for the 7% and 15% damping cases under a long-period motion. Elasto-plastic deformation is observed. The analysis also indicates that the isolated structure behaves as a single degree freedom system. The relative displacement between upper and lower mat can be approximately represented by the spectral displacement at the frequency of the isolated structure as shown in Table 2. The calculated acceleration response is, however, much less than the spectral acceleration as shown in Table 1. This may be attributed to the elasto-plastic deformation in the bearings.

In summary, long-period earthquake motions increase the seismic response of the structure, including both structural acceleration and relative displacement between the upper and lower mats. However, the relative displacement, which is crucial to structural integrity of bearings, can be effectively reduced by increasing the isolator damping.

3 NONLINEAR MATERIAL PROPERTIES OF RUBBER AND SOIL

Both soil and rubber are strain-dependent nonlinear materials. Their response is determined mainly by the shear modulus and damping characteristics under cyclic loading conditions. Most soils have curvilinear stress-strain relationships as shown in Fig. 9; the shear modulus is usually expressed as the Secant modulus determined by the extreme points on the hysteresis loop while the damping factor is proportional to the area inside the hysteresis loop. Figure 10(a) shows the nonlinear soil shear modulus vs. shear strain curves for two types of soil, while Fig. 10(b) shows the corresponding nonlinear soil damping vs. shear strain curves. The soil shear modulus decreases as the shear strain increases. On the other hand, the soil damping increases as shear strain increases. Soil shear strain usually ranges from 0% up to 10%, while damping ranges from 2% to 30% of critical damping depending on shear strain. Figure 11 shows the force-displacement relationship for the rubber. Figures 12(a) and 12(b) show the shear modulus vs. shear strain curve and equivalent viscous damping vs. shear strain for the typical rubber bearing material. The shear modulus and viscous damping of rubber material decrease as the shear strain increases. The shear strain of rubber can reach to 200% or even higher. The material properties of rubber and soil are summarized in Table 3.

4 CONCLUSIONS

The preliminary analysis indicates that the long-period earthquake motions increase the structural accelerations and relative displacements between the upper and lower mats of the seismic-isolated structure. The relative displacement can be effectively reduced by increasing the isolator viscous damping. The isolated structure behaves as a single degree freedom system. The relative displacement between upper and lower mats can be approximately represented by the spectral displacement at the frequency of the isolated structure. Future analysis should include soil-structure interaction effects, considering the nonlinear effects of soil.

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2. Proceedings of the First International Seminar on Seismic Base Isolation for Nuclear Power Facilities (1989). CONF-8908221, August 21-22, 1989.

3. Shiojiki, H. et al. (1989). Seismic Isolation for FBR - Preliminary Study, Seismic, Shock and Vibration Isolation - 1989, ASME PV&P, Special Publication, Vol. 181.

Table 1. Maximum acceleration (g) at top of the reactor building of various cases

	Case 1	3% Damping Spectral Accel. at 0.75 HZ	Case 2	Case 3	7% Damping Spectral Accel. at 0.75 HZ
Conventional Motion	0.147 g	0.24 g	0.13 g	0.12 g	0.18 g
Long-Period Motion No. 1	0.21 g	0.48 g	0.25 g	0.25 g	0.36 g
Long-Period Motion No. 2	0.27 g	0.48 g	0.25 g	0.23 g	0.36 g
Long-Period Motion No. 3	0.26 g	0.52 g	0.24 g	0.21 g	0.34 g

Case 1: 3% structural and isolator damping
Case 2: 7% structural and isolator damping
Case 3: 7% structural damping and 15% isolator damping

Table 2. Relative displacement (in.) between upper and lower mats of various cases

	Case 1	3% Damping Spectral displ. at 0.75 HZ	Case 2	Case 3	7% Damping Spectral displ. at 0.75 HZ
Conventional Motion	4.4"	4"	4.4"	3.5"	3.5"
Long-Period Motion No. 1	8.4"	8"	7.9"	5.6"	6"
Long-Period Motion No. 2	6.3"	6"	5.1"	3.0"	5"
Long-Period Motion No. 3	7.4"	8"	5.4"	4.0"	5.5"

Case 1: 3% structural and isolator damping
Case 2: 7% structural and isolator damping
Case 3: 7% structural damping and 15% isolator damping

Table 3. Similarities between rubber bearing and soil

	Soil	Rubber
Material	Viscoelastic; strain dependent	Viscoelastic; strain dependent
Shear Strain Range	0% ~ 10%	0% ~ 200%
Shear Modulus	Shear modulus decreases as shear strain increases; sensitive to shear strain	Same as soil; highly nonlinear between 0% to 25% of shear strain
Damping	Damping increases as shear strain increases; damping sensitive to shear strain; damping ranges from 2% to 20%	Damping decreases as shear strain increases; not very sensitive to shear strain; damping ranges from 10% to 15%

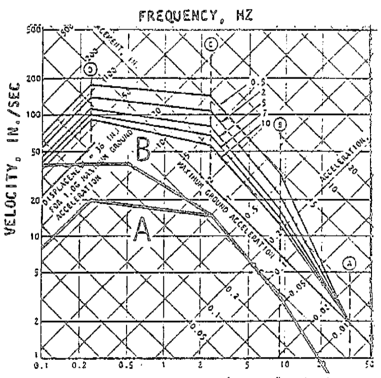

Fig. 1 Conventional (A) and Long-period Spectrum (B)

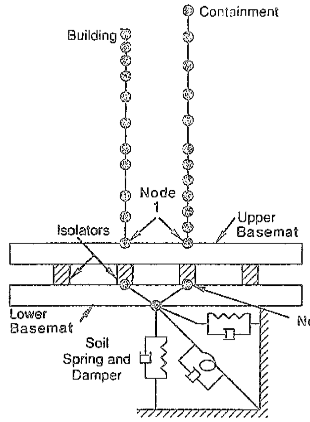

Fig. 5 Reactor Building Model

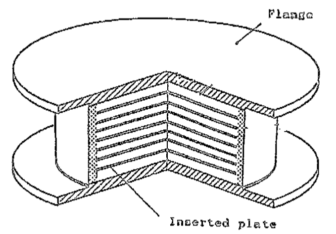

Fig. 6 Steel-laminated High-Damping bearing

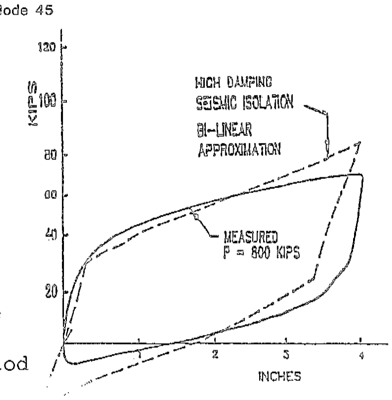

Fig. 7 Bi-Linear force-displacement curve for Isolator

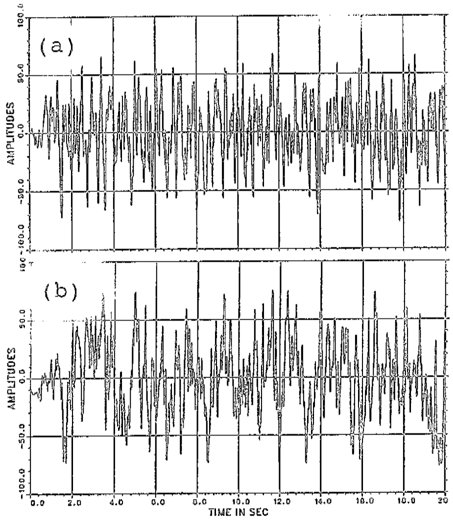

Fig. 2 Accel. History of (a) Conventional and (b) Long-period Motion

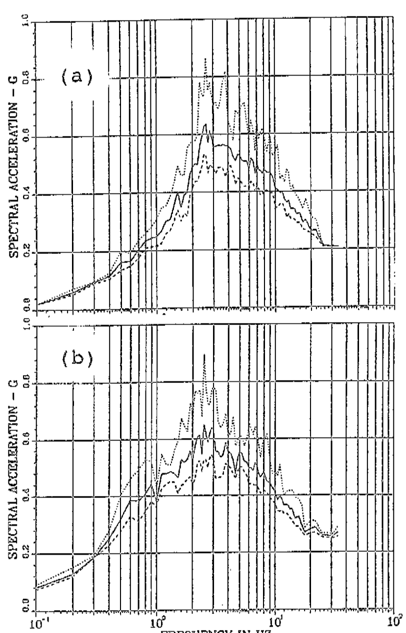

Fig. 3 Accel. Spectrum of (a) Conventional and (b) Long-period Motion

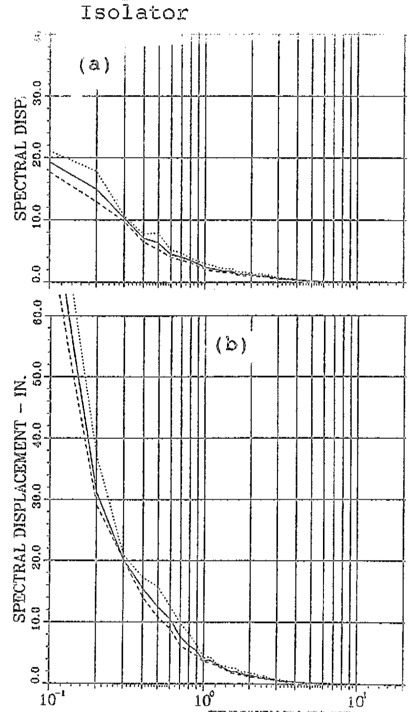

Fig. 4 Displacement Spectrum of (a) Conventional and (b) Long-period Motion

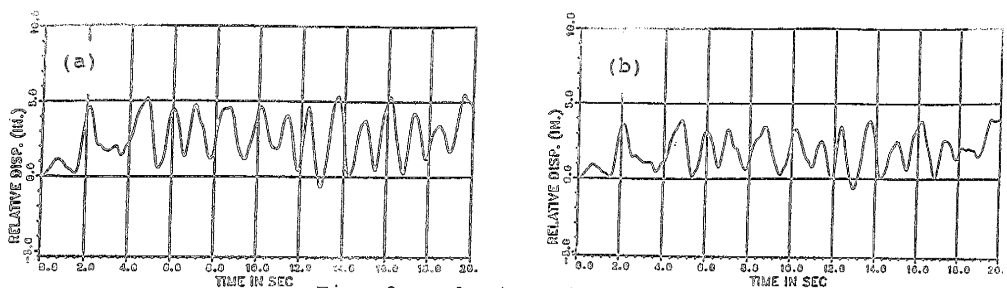

Fig. 8 Relative Displacement
(a) 7% Isolator Damping
(b) 15% Isolator Damping

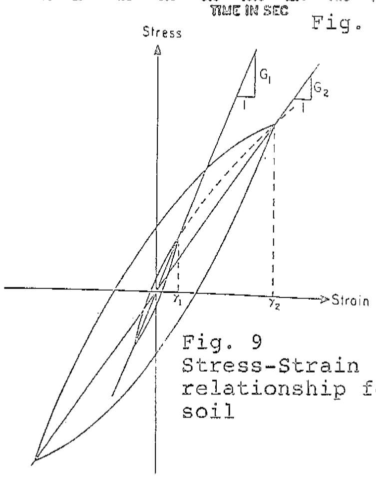

Fig. 9 Stress-Strain relationship for soil

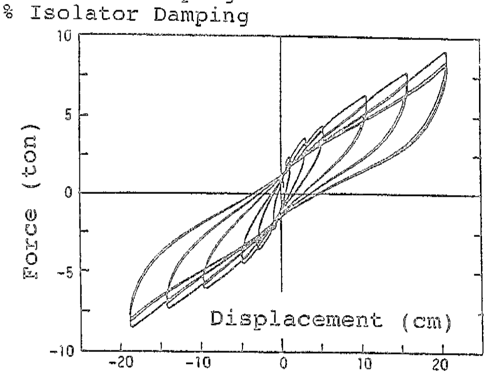

Fig. 11 Force-Displacement Curve for Rubber

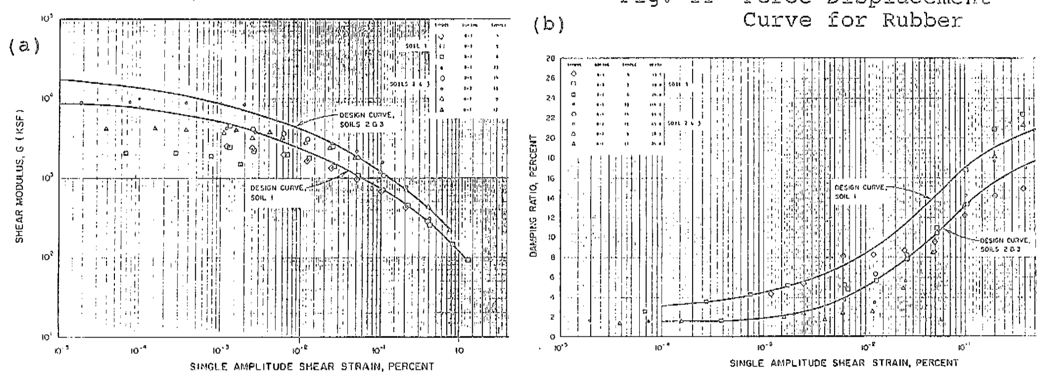

Fig. 10 (a) Shear strain vs. shear modules and (b) shear strain vs. Damping for Soil

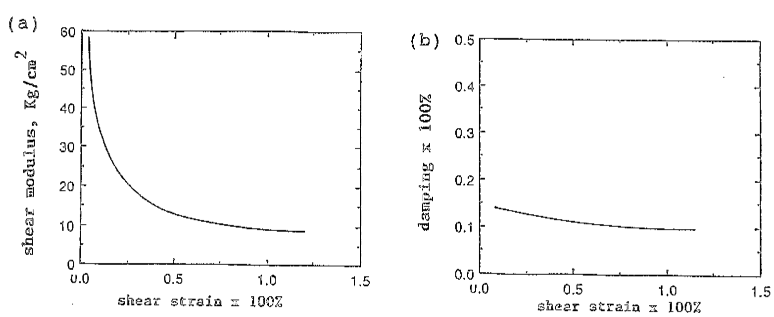

Fig. 12 (a) Shear strain vs. shear modules and (b) shear strain vs. Damping for Rubber