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Numerical Simulation of Seismic Response of a Base Isolated Building with Low Shear Modulus Rubber Isolators*

by

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ABSTRACT

This paper describes seismic-response simulations of a base-isolated building subjected to actual earthquakes using the 3-D computer program, SISEC, developed at Argonne National Laboratory. The isolation system consists of six medium shape factor, high damping, and low shear modulus rubber bearings. To ensure the accuracy of analytical simulation, recorded data of full-size reinforced concrete structures located in Sendai, Japan are used as the benchmarks for comparisons of numerical simulations with observations.

Results obtained from both analytical simulations and earthquake observations indicate that the advantage of base isolation in mitigating the acceleration of superstructure is very pronounced. For the two representative earthquakes, one had the strongest ground motion and the other one had similar magnitudes as the rest of the earthquakes recorded at the test site, the simulated accelerations at the roof level of the isolated building are about 20% to 30% of the ordinary building accelerations. Also, results reveal that for both ordinary and base-isolated buildings the computed accelerations agree reasonably well with those recorded.

INTRODUCTION

Seismic isolation represents a significant engineering breakthrough in structural designs due to its capabilities of protecting structures and their contents from earthquake damage. One main concept in base isolation is to reduce the fundamental frequency of structural vibration to a value lower than the energy-containing frequencies of earthquake ground motions. Another purpose of an isolation system is to provide a mechanism for energy dissipation and to reduce the transmitted accelerations to the superstructure. In other words, by using base-isolation devices at the foundation of a structure, the structure is essentially decoupled from ground motion during earthquakes.

An international cooperation program was initiated in September, 1988 by Argonne National Laboratory (ANL) of the USA and Shimizu Corporation of Japan for studying the response of isolated structures under actual earthquakes. Within the program agreement, Shimizu provided their test facility and earthquake data collection while ANL supplied the isolation bearings to be installed at the test facility and performed most of the analytical simulations utilizing the ANL developed 3-D computer program, SISEC (Seismic Isolation System Evaluation Code) (Wang et al., 1991).

The major task of the joint program is achieved through the unique design of the test facility, located at Tohoku University in Sendai, Japan (about 200 miles north of Tokyo). The test facility consists of two identical full-size three-story buildings built side-by-side; one structure is seismically isolated and the other is ordinary founded. The facility can easily adapt to a variety of seismic isolated systems. Since Sendai is quite active seismically, considerable data can be obtained in a relatively short period of time.

To ensure the accuracy of the analytical simulation, recorded data of full-size reinforced concrete structures are used as the benchmarks for comparisons of code simulations with

observations. Also, numerical calculations were carried out for the ordinary building, aimed at studying the relative responses of these two structures.

Two high-damping isolation systems, designed by ANL, were installed in the isolated building of the test facility. The first one, installed in April 1989, was a high shape factor, high shear modulus rubber bearing system aimed for medium and large earthquakes. From April 1989 to July 1990 thirty-seven (37) earthquakes have been recorded. Detailed responses of the test facility were analyzed and reported (Wang & Gvildys 1991; Uras 1993). The second one was a medium shape factor, low shear modulus bearing system designed for a wide range of earthquakes, including small earthquakes. This system was installed in October 1990. This paper addresses the response simulations of the low shear modulus bearing system.

From November 1990 to March 1991, seven earthquake motions were observed at the test facility (Kuroda et al., 1991). Complete records of two representative earthquakes, #42 and #44, are used in this paper. In the analysis, 3-D models were developed for simulating the seismic responses of the ordinary and isolated structures. Correlations of observed and calculated accelerations at all instrument locations are made. The advantages of the base-isolation system in reducing the seismic accelerations is also discussed.

GENERAL DESCRIPTION

Two test buildings, one conventionally designed and other base-isolated, were constructed side by side at Tohoku University in Sendai, which is in the northern part of Japan. The test buildings consist of two full-size, three-story reinforced concrete structures. The dimensions and construction details of the super-structure were exactly the same for both buildings. The buildings were constructed as rigid frame structures with outer walls made of light weight concrete panels. The plan dimensions of the building are 6 by 10 meters (19.685 by 32.808 ft). The total combined floor area is 180 m² (1937.49 ft²). The test buildings were completed in May 1986.

Figure 1 shows a general view of the test buildings. The building on the left is the ordinary one, whereas on the right is the base-isolated structure. The plan and elevation of the test structures given in Fig. 2 show six isolator bearings installed in the base-isolated building. Note from this figure that the ordinary building is surrounded by backfilled soil below the ground level and that the basement wall is made of reinforced concrete. The presence of soil embedment and concrete wall definitely will have certain mitigating effects on the building response. As for the isolated building, ample space is provided around the side of the basement wall to allow unrestricted movement of the superstructure. The base-isolation system consists of six laminated steel-rubber bearings.

The isolation system of the base isolated building consists of six identical bearings (Fig. 3) designed with a medium shape factor and molded with a high damping, low shear modulus rubber. These bearings are laminated composites with 12 layers of rubber and 11 layers of steel plates (shims) manufactured by Rubber Consultants, UK. The nominal vertical load is 92.61 kips, corresponding to 621 psi vertical pressure. The outer diameter and overall height of the

bearing are 375 and 206 mm (20 and 11 3/16 in), respectively. The design isolation frequency of the bearings, corresponding to the 100% shear strain, is 0.40 Hz. Fixed flange type of joint is used at the top and bottom plates of the bearings which transfers loads from the structure to the bearing and to the foundation. Note that the U.S. bearings previously installed in the Sendai isolated building between April 1989 and July 1990 were high-shape-factor bearings (Wang & Gvildys, 1991) with 33 rubber layers and 32 shims.

Since the installation of ANL-designed isolation bearings, 7 earthquakes have been observed from November 1990 through March 1991 at the test facility. Records of these events have been transmitted to ANL. Since the entire acceleration records are quite extensive, only two representative earthquake records, i.e., records #42 and #44, are used for the discussion of results presented in this paper. These two earthquake records are chosen because record #42 earthquake had the strongest ground motion, and #44 had similar magnitude as other earthquakes recorded at the test site.

MATHEMATICAL MODEL

Three-dimensional frame models are used in the SISEC code simulations for both conventional and base-isolated buildings. In the analyses, beams, columns, and girders are all modeled by 3-D beam elements with six degrees of freedom per node to account for the translations and rotations generated from seismic events. Stiffness of the outer walls and partitions that are not structurally connected to the beams and girders are neglected in the calculation. However, their masses are appropriately lumped to the element nodal points, so that their inertia effects are included in the analysis.

The mathematical models of both ordinary and base-isolated buildings are given in Fig. 4. These two models are almost identical except that different modeling techniques are used for the substructure connecting the basement slab and the first floor. More specifically, major difference is in the middle portion of the support columns where the isolator is located. For the ordinary building, each basement column is represented by three beam elements in which the stiffness of the basement reinforced concrete wall is included. For the isolated building, on the other hand, the isolator is modeled by two spring elements; one linear spring and one nonlinear elastoplastic spring to simulate, respectively, the vertical and horizontal responses of the isolator. Two beam elements, similar to those columns of the superstructure are then utilized above and below the isolator to model the reinforced concrete pedestals.

To facilitate the numerical simulation, separate models are employed to analyze the horizontal responses in the transverse (X) and longitudinal (Y) directions. In these models only input accelerations at the basement nodes and building boundary conditions are different due to differences in the direction of seismic excitation. Other input data are identical.

In calculating the horizontal response of the isolator a bi-linear force-displacement constitutive relationship is used for the nonlinear spring element. This relationship is determined

from the dynamic tests of the ANL bearings conducted by the University of California at Berkeley (Kelly, 1991).

RESULTS AND DISCUSSION

Data of two representative earthquakes, #42 and #44, are used here to study the building response characteristics. In simulating the response of the ordinary and isolated buildings, the X (transverse) and Y (longitudinal) component accelerations observed at the center of the basement of the isolated building are utilized as input to the basement structural nodes. The computed accelerations are then compared with those of observations. Due to space limitations, emphasis is placed on earthquake record #44.

Earthquake #42

This earthquake occurred on January 16, 1991. It has a magnitude of 4.8 and an epicentral distance of 48 km. Figure 5 depicts the two components of accelerations at the basement.

For simplicity, comparison of observed and calculated peak accelerations at the first floor and the roof level of both the ordinary and isolated buildings for earthquake record #42, are given in Table 1. Deviations of calculated value with respect to the observed peaks is also listed. As can be seen for the ordinary building, the error is about 3%. For the isolated building, the maximum deviation is about 20%. The average errors for the ordinary and isolated buildings are 12% and 13%, respectively.

With the adaptation of the medium shape factor-high damping-low shear modulus bearings, the effects of base isolation system in mitigating the seismic response of the superstructure is quite evident. One convenient way to demonstrate the advantage of the base isolation is to compare the accelerations given in Table 2, in which the peak values for both ordinary and isolated buildings are listed. The trend of acceleration reduction for the isolated structure is quite clear. For instance, in the numerical simulation, the transverse direction accelerations at the first floor of the isolated building is about 54% of the ordinary building, whereas in the recorded data it is about 66%.

At the roof level, the advantage of base isolation becomes more pronounced. The analytical results indicate that, in the transverse and longitudinal directions, the accelerations of the isolated building are about 23% and 27% of the ordinary building accelerations. In the observation data, the acceleration ratios are about 26% and 33%. This further demonstrates that as the floor elevation increases the degree of acceleration reduction also increases.

To illustrate the advantages of the base-isolation system, Figs. 6 and 7 depict the observed and simulated longitudinal accelerations at the roof level of both the ordinary and isolated buildings, respectively. Comparison of the peak values of the acceleration indicates that because

of the flexibility of the isolators the accelerations for the base-isolated building are greatly reduced.

The base isolation system also has the effect of reducing the relative displacement experienced during the earthquake. In the SISEC code simulation of the ordinary building, the displacements at the roof level relative to the basement in the transverse and longitudinal directions are 0.32 and 0.74 in., respectively. However, for the isolation building the roof displacements are only 0.0125 and 0.0153 in., respectively.

Earthquake #44

This earthquake occurred quite near the test building on March 17, 1991. It had a magnitude of 4.1 and epicentral distance of about 70 km from the test facility. The earthquake had the same order of magnitude when compared with other earthquakes detected between November 1990 and March 1991.

Figure 8 provides observed accelerations in the transverse (X) and longitudinal (Y) directions at the basement of the isolated building. The maximum accelerations corresponding to these two directions are 0.52 and 0.54 in/sec² (1.32 and 1.37 gal), respectively. These values are smaller than those of earthquake #42. These recorded acceleration time histories were used in the SISEC code time-history analyses of building responses.

Ordinary Building. The observed and calculated transverse (X-direction) accelerations at the first floor are given in Fig. 9. Good comparison has been found, not only the peak values and the times of occurrence, but also the response shapes and characteristic frequencies. Figure 10 depicts the comparison of roof accelerations in the transverse (X) direction. As can be seen from these two figures, both accelerations correlated excellently with each other. The maximum accelerations only differ by 4%. Also, it is noted from the analytical results of FFT frequency plots that the roof vibrates with a frequency of approximately 3.50 Hz, whose value compares satisfactorily with the field test result of 3.63 Hz obtained by the Shimizu Corporation of Japan.

In the longitudinal (Y) direction, the recorded and simulated acceleration histories at the first floor are given in Fig. 11. Reasonable comparison of the accelerations can be seen from this figure, although a larger deviation is observed in the peak values.

At the roof level, the observed and calculated accelerations are presented in Fig. 12. It shows that major seismic events occur between 6 to 16 seconds and gradually damp out around t=20 sec. Exceptionally good comparison is found for the peak accelerations at the roof level, which have values of 2.14 and 2.08 in/sec² (5.43 and 5.28 gal), respectively.

Isolated Building. Input accelerations for simulating the transverse (X) and longitudinal (Y) responses of the isolated building have been presented previously in Fig. 8. The two components of ground acceleration have dominant frequencies of 2.40 and 2.06 Hz, respectively. Numerical simulations are carried out with the SISEC code through 5000 cycles of computation with a 0.01 sec constant integration step.

In the transverse direction, the recorded and simulated accelerations at the first floor are shown in Fig. 13. Good agreement again has been found from these acceleration responses. Peak accelerations compare well; nevertheless, the simulated value is underpredicted by 17%. Again, analytical simulation closely predicts the dominant frequency of 1.07 Hz, but fails to compute the higher frequency component with a value of 5.5 Hz.

Figure 14 depicts the recorded and calculated acceleration histories at the roof of the isolated building. Better correlation of the acceleration pulse is obtained in which the maximum acceleration is only underpredicted by about 7%. The observed maximum frequency is 1.03 Hz, compared to 1.18 Hz from the analytical simulation.

In the longitudinal direction, the observed and calculated accelerations at the first floor and roof are compared in Figs. 15 and 16. The trends of acceleration histories at the corresponding location agree well, except that the high frequency component is not present in the analysis. The deviations between the observed and simulated peak values are 18 and 21%, respectively, at the first floor and roof. At these two locations, the calculated dominant frequency is found to be 1.16 Hz. The 6.87 Hz frequency components embedded in the observation is not visible in the longitudinal building response.

Table 3 lists the comparison of recorded and calculated maximum accelerations for earthquake record #44. It again shows that for the ordinary building the computed roof acceleration agrees excellently with those observed. For the isolated building, in general, the analytical results underpredict the observed. The average deviations for the ordinary and isolated building are 17 and 16%, respectively.

Effects of Base Isolation. The advantage of base-isolation system again is clear for earthquake #44, even if it was of very small magnitude. From the maximum accelerations given in Table 4, one can compute the ratio of acceleration for the isolated building relative to the ordinary building. In the SISEC code simulations of transverse and longitudinal seismic response, accelerations computed at the first floor of the isolated building are about 50% and 37% of the ordinary building. The recorded data show that the acceleration ratios are about 71% and 65%, respectively.

At the roof level, the mitigating effect is very significant. In fact, in both the transverse and longitudinal directions accelerations of the isolated building are about 16-20% of the ordinary building. This means that even for a minor tremor, a factor of 5 in the acceleration reduction at the higher elevation can be achieved by using this low-shear-modulus isolation system.

Regarding the reduction of relative displacement, the calculated horizontal displacements in the transverse and longitudinal directions at the roof level are 0.1700 and 0.1715 in. for the ordinary building. However, for the isolated building, the corresponding maximum displacements are only 0.0085 and 0.0063 in., respectively.

CONCLUSIONS

From the results of actual recorded earthquake data and SISEC code simulations, several conclusions can be drawn:

(1) With the use of medium shape factor-high damping-low shear modulus bearings, the advantage of isolation system in mitigating the acceleration response as well as in protecting structure and its contents is very significant even for small earthquakes. For instance, for earthquake #42, computed accelerations in the transverse and longitudinal directions of the isolated building are 1.59 and 1.94 gal (see Table 1) compared to 6.96 and 7.16 gal for the ordinary building. This means that an acceleration reduction factor of 3 is associated with the isolated building. For earthquake #44, we have found that the roof accelerations of the isolated building is about 5 times smaller than the ordinary building.

(2) The SISEC code can reproduce the general shape of the acceleration responses, both for the ordinary and base-isolated buildings. The analysis accurately predicts the peak accelerations and the times of occurrence.

(3) The NSF/ANL bearings installed in the isolated building in Sendai, Japan are very effective for mitigating the earthquake hazards. For the small earthquakes analyzed here, #42 and #44, the use of the low shear modulus bearings has resulted in small displacements and accelerations of the superstructure. Both observed and analytical results clearly indicate that the NSF/ANL bearings have the desired effective characteristics.

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Table 1. Comparison of Observed and Calculated Maximum Accelerations (Earthquake #42)

Location	Direction	Ordinary Building			Isolated Building		
		Obs. gal	Cal. gal	Diff. %	Obs. gal	Cal. gal	Diff. %
Roof	T(X)	7.18	6.96	-3.1	1.87	1.59	-15.1
	L(Y)	7.29	7.16	-1.7	2.46	1.94	-20.8
First Floor	T(X)	2.10	2.45	+14.5	1.39	1.33	-4.2
	L(Y)	2.79	3.58	+28.3	1.90	1.70	-10.6
Basement	T(X)				2.19		
	L(Y)				2.70		

T: Transverse

L: Longitudinal

Table 2. Comparison of Accelerations of Isolated and Ordinary Buildings (Earthquake #42)

Location	Direction	Ordinary Building, A_o		Isolated Building, A_i		Accel. Ratio, A_i/A_o	
		Obs. gal	Cal. gal	Obs. gal	Cal. gal	Obs.	Cal.
Roof	T(X)	7.18	6.96	1.87	1.59	0.26	0.23
	L(Y)	7.29	7.16	2.46	1.94	0.33	0.27
First Floor	T(X)	2.10	2.45	1.39	1.33	0.66	0.54
	L(Y)	2.79	3.58	1.90	1.70	0.68	0.47
Basement	T(X)			2.19			
	L(Y)			2.70			

T: Transverse

L: Longitudinal

Table 3. Comparison of Observed and Calculated Maximum Accelerations
(Earthquake #44)

Location	Direction	Ordinary Building			Isolated Building		
		Obs. gal	Cal. gal	Diff. %	Obs. gal	Cal. gal	Diff. %
Roof	T(X)	8.73	8.56	-1.8	1.44	1.34	-6.8
	L(Y)	5.43	5.27	-2.9	1.09	0.86	-21.3
First Floor	T(X)	1.66	1.95	+17.8	1.19	0.97	-18.2
	L(Y)	1.43	2.05	+43.1	0.93	0.76	-18.1
Basement	T(X)				1.32		
	L(Y)				1.35		

T: Transverse

L: Longitudinal

Table 4. Comparison of Accelerations of Isolated and Ordinary Buildings (Earthquake #44)

Location	Direction	Ordinary Building, A_o		Isolated Building, A_i		Accel. Ratio, A_i/A_o	
		Obs. gal	Cal. gal	Obs. gal	Cal. gal	Obs.	Cal.
Roof	T(X)	8.73	8.56	1.44	1.34	0.16	0.16
	L(Y)	5.43	5.27	1.09	0.86	0.20	0.16
First Floor	T(X)	1.66	1.95	1.19	0.97	0.71	0.50
	L(Y)	1.43	2.05	0.93	0.76	0.65	0.37
Basement	T(X)			1.32			
	L(Y)			1.35			

T: Transverse

L: Longitudinal

Fig. 1 General view of test building

Fig. 2 Plan and elevation views of test building

Fig. 3 Bearing Dimensions (unit: mm)

NO ISOLATION

WITH ISOLATION

Fig. 4 Mathematical Model of Ordinary and Isolated Buildings

Fig 5. Acceleration histories used in the Numerical simulations of Earthquake # 42 (Left: transverse, right: Longitudinal)

Fig. 6 Comparison of Longitudinal accelerations at the Roof Level of the ordinary building (Left: observed, right: calculated, EQ. #42)

Fig. 7 Comparison of Longitudinal accelerations at the Roof Level of the Isolated Building (Left: observed, right: calculated, EQ. #42)

Fig 8. Acceleration histories used in the Numerical Simulations of earthquake # 44 (Left: transverse, right: Longitudinal)

Fig 9 Comparison of transverse accelerations at the first floor of the ordinary building (EQ. #44, Left: observed, right: calculated)

Fig. 10. Comparison of transverse accelerations at the roof level of the ordinary Building (EQ. #44, Left: observed, right: calculated)

Fig. 11. Comparison of Longitudinal accelerations at the first floor of the ordinary Building (EQ. #44, Left: observed, right: calculated)

Fig. 12. Comparison of Longitudinal accelerations at the roof level of the ordinary building (EQ. #44, Left: observed, right: calculated)

Fig. 13. Comparison of transverse Accelerations at the first floor of the isolated building (EQ. #44, Left: observed, right: calculated)

Fig.14. Comparison of transverse accelerations at roof level of the isolated Building (EQ. #44, left : observed, right : calculated)

Fig.15 Comparison of Longitudinal accelerations at the first floor of the isolated building (EQ. #44, left : observed, right : calculated)

Fig.16 Comparison of Longitudinal accelerations at the roof level of the isolated building (EQ. #44, Left: observed, right : calculated)

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