Experimental Study of Seismic Reduced Performance of Series Isolation System

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Abstract—In order to study the seismic reduced performances (SRP) of series isolation systems (SIS) under multi-dimensional seismic excitation (MDSE), a series of shaking table tests had been conducted for the SIS model. The two groups of seismic waves, including the near fault ground motion and far fault ground motion were firstly chose from the Chichi earthquakes as the input. The responses of SIS under the different seismic waves were predicted by response spectrum method. The paper discussed the effect of earthquake intensity on SRP of SIS under different input patterns, and further analyzed the effect of near fault ground motion and far fault ground motion on the SRP, and compared to the predicted results. The results show that, compared to near fault ground motion, the seismic reduced ratio (SRR) of SIS is better under the far fault ground motion. The SRR of SIS increases with increasing the earthquake intensity, but it is obvious under near fault ground motion. The test results are consisted with the predicted results. The SRRs are small for the different shaking table tests, so the SRP of SIS is better. Moreover, the SRP under 2-dimensional seismic excitation is consistent with that under 3-dimensional seismic excitation with increasing the earthquake intensity.

Keywords—series isolation system; seismic reduced performance; shaking table test; response spectrum method; earthquake intensity; near fault ground motion; multi-dimensional seismic excitation

I. INTRODUCTION

With the rapid population increase and the construction of isolated structure is gaining acceptance. Series isolated structure is widely applied in isolated structure including

isolated buildings and isolated bridges. SIS is an important part of series isolated structure. Its SRP is discussed under the MDSE. The theoretical and experimental research on the SIS is rare in domestic and foreign research works. Zhou Xiyuan et al. (1999) established an analysis model of series isolation system based on the Harings and Gent researches[1]. DU Yongfeng et al. (2011) did the theoretical analysis by matrix transfer method and static experiment for scale model of SIS, and analyzed the collapse of series isolation structure under the MDSE[2, 3]. WU Yingxiong et al. studied the dynamic properties and performance analysis of isolation technology for a first-floor isolation structure[4]. Many shaking table tests for isolation structure were carried out and some good conclusions were obtained[5~9]. On the basis of previous research, this paper aims at investigating the performance of SIS in the isolated structure to do shaking table tests under the 2-dimensional seismic excitation (2DSE) and 3-dimensional seismic excitation (3DSE) and analyzed its SRP using the SRR and discussed the influence of earthquake intensity on its SRP, and gave some good conclusions.

II. DESIGN OF TEST MODEL

The test model is shown in Fig. 1. It consists of one plate and four series isolation systems composed of lead rubber bearing (LRB) and reinforcement concrete (RC) column. The upper total weight is up to 10t. The parameters of LRB, RC column and concrete plate are shown in Tab. 1 and Tab. 2, respectively.

Figure 1. Test model of SIS.

TABLE I. PARAMETERS OF LRB

Type	D ₁ (mm)	D ₀ (mm)	l _r (mm)	P _b (MPa)	Q _d (kN)	K _d (kN/mm)	K _{eq} (kN/mm)
LRB90	90	15	18	4-5	1.409	0.139	0.217

Note: D₁—diameter of LRB ,D₀—diameter of lead, l_r—total height of the rubber layer , P_b—standard pressure , Q_d—yield load , K_d—yield stiffness, K_{eq}—equivalent horizontal stiffness when the horizontal deformation is 100%

TABLE II. PARAMETERS OF RC COLUMN AND PLATE

Type of materials	Materials performance				RC column			Concrete plate		
	E (MPa)	v	f _t (MPa)	f _c (MPa)	L _c (mm)	B _c (mm)	H _c (mm)	L _p (mm)	B _p (mm)	H _p (mm)
concrete	30000	0.2	1.43	14.3						
Longitudinal bar	200000	0.3	300	300	150	150	1000	2800	2800	400
Stirrup	200000	0.3	270	270						

Note: E—elastic modulus, v—poisson ratio, f_t—tensile strength, f_c—compressive strength, L_c, B_c, H_c—length, width and height of RC column respectively, L_p, B_p, H_p—length, width and height of concrete plate respectively.

III. EQUIVALENT PERIOD OF TEST MODEL

The SIS consists of lead rubber bearing and RC column, so its equivalent horizontal stiffness can be approximately obtained by the following formula.

$$K_{eqSIS} = K_{eqLRB} \frac{K_{eqRC}}{K_{eqLRB} + K_{eqRC}} \quad (1)$$

Where, K_{eqSIS} is the equivalent horizontal stiffness of SIS, and K_{eqLRB} is the equivalent horizontal stiffness of LRB, and K_{eqRC} is the equivalent horizontal stiffness of RC column, K_{eqLRB} and K_{eqRC} are computable by (2) and (3), respectively.

$$K_{eqLRB} = K_d + \frac{Q_d}{d} \quad (2)$$

$$K_{eqRC} = \frac{3E_c I_c}{L^3} \quad (3)$$

Where, d is the horizontal displacement of LRB, E_c is the elastic modulus of concrete, I_c is the moment of inertia of RC column.

Its equivalent period can be obtained by (4).

$$T_{eqSIS} = 2\pi \sqrt{\frac{M}{K_{eqSIS}}} \quad (4)$$

Where, T_{eqSIS} is the equivalent period of SIS, M is the upper total weight of SIS.

The displacement response of SIS is different under the seismic waves. The horizontal stiffness of SIS varies with

its shear deformation, then, the period of SIS changes with the deformation. The equivalent period of SIS can be calculated by (4). The results are listed in the tab. 3. It can be seen from the tab. 3. The period increases with the increasing of the shear deformation and ranges from 0.5-0.8s when the shear deformation varies from 25%-250%.

TABLE III. THE EQUIVALENT PERIOD OF SIS

shear deformation(%)	25	50	100	200	250
T _{eq} (S)	0.538	0.636	0.723	0.788	0.804

IV. SELECTION AND ANALYSIS OF SEISMIC WAVES,

The two groups of seismic waves, which are named CC1 and CC2, are selected from the Chichi earthquake in this paper, and the CC1 has three components and the CC2 has two components. There are two input patterns in shaking table test, including two components (X direction and Y direction) and three components (X direction and Y direction and Z direction). The parameters of seismic waves and input patterns are shown in Tab. 4 and Tab. 5, respectively. The seismic waves with the peak values of 100 gal, 150 gal, 200 gal, 300 gal and 400gal are adopted as excitations for shaking table tests. Acceleration time history of seismic waves and the response spectra are shown in Fig. 2 and Fig. 3, respectively. It can be seen in Fig. 2 that the acceleration of CC1 is big and appears relatively concentrated. However, the acceleration of CC2 is small and appears relatively discrete. It can be seen from Fig. 3, when the peak acceleration of CC1 in the response spectra appears, the period is at 0.35s, and the period of its dominant effect ranges from 0.3s to 1.5s. When the peak acceleration of CC2 in the response spectra appears, the period is at 0.14s, and the period of its dominant effect ranges from 0.1s to 0.8s. The equivalent period of SIS mainly distributes at the range of 0.5s-0.8s, the time step of nature seismic waves is scaled from 0.02s to 0.01s in the shaking table test, and natural period of response spectra has the same change. The equivalent period of SIS is at range of the dominant effect of

near fault ground motion, therefore, it can be predicted that its seismic response of SIS is larger, and its seismic reduced

effect is lower.

Figure 2. Time history of acceleration: (a) CC1, (b) CC2.

Figure 3. Response spectra (5% damping ratio): (a) CC1, (b) CC2.

TABLE IV. PARAMETERS OF SEISMIC WAVES

Earthquake waves	station	Year	Magnitude	Rupture distance (km)	Peak acceleration (g)		
					NS	EW	UD
CC1	CHY028	1999	7.62	3.1	0.821	0.653	0.337
CC2	CHY028	1999	5.9	46	0.044	0.037	—

TABLE V. INPUT PATTERN

No.	Main direction	Input pattern(Input direction)	
		2DSE(X+Y)	3DSE(X+Y+Z)
1	CC2-NS	CC2-NS+CC2-EW	—
2	CC2-EW	CC2-EW+CC2-NS	—
3	CC1-NS	CC1-NS+CC1-EW	CC1-NS+CC1-EW+CC1-UD
4	CC1-EW	CC1-EW+CC1-NS	CC1-EW+CC1-NS+CC1-UD

V. ANALYSIS ON THE SRP OF SIS

In order to study the SRP of SIS, the SIS model has been carried out through the shaking table test. The effect of main factors on the SRP of SIS, including the near fault ground motion, earthquake intensity and multi-dimensional seismic excitation is analyzed. The accelerations of the three key positions are chosen from the testing data, which include the surface of shaking table, the top of concrete plate. The SRP of SIS is analyzed by using the SRR α calculated by (5) and

the amplification coefficient β calculated by (6). Where S_a is the peak value of absolute acceleration obtained from the top of concrete plate and u_g is the peak value of absolute acceleration obtained from the surface of shaking table.

$$\beta = \frac{S_a}{u_g} \quad (5)$$

$$\alpha = 1 - \beta \quad (6)$$

The related curves of earthquake intensity and SRR of BD under the 2DSE are shown in Fig. 4. It can be seen that the SRR of SIS under the far fault ground motion is better than that under the near fault ground motion, and the value of SRR under the far fault ground motion is approximately 2 to 1.3 times at the range from 0.1g to 0.5g. It is consisted with the analysis results based on the response spectrum method. In the meantime, the SRR increases with increasing earthquake intensity and change laws of SRR under the near fault ground motion are much clearer. It shows that SRP is better with increasing the earthquake intensity and it is not the same for different ground motions. Moreover, it is clear that the SRR of SIS is different for the different components of seismic wave at the same station. As shown in Fig. 5. It illustrates that four main directions in all input patterns are CC2-NS, CC2-EW, CC1-NS and CC1-EW, respectively. The average value of SRR is 0.7, 0.72, 0.49 and 0.43 in turn, and the biggest difference is 0.036, 0.028, 0.204 and 0.162 in turn. Obviously, the SRR under the near fault ground motion is less than that under the far fault ground motion, and its SRP is worse. It shows that the SRP is not only affected by earthquake intensity, but also by the characteristics of seismic wave.

Figure 4. Related curves between SRR α and earthquake intensity under the 2DSE.

Figure 5. The average value of SRR α under the 2DSE.

Figure 6. Amplification coefficient β of BD for different input patterns

Fig. 6 shows the related curves between amplification coefficient and earthquake intensity of key positions BD under different input patterns of CC1. The amplification coefficient of BD decreases with increasing the earthquake intensity under the 2DSE and 3DSE. The change laws of curves are basically the same. The curves of the amplification coefficient are closed, but it is slightly lower under 3DSE. The SRP is better with increasing the earthquake intensity under the 3DSE.

VI. CONCLUSIONS

The following conclusions are obtained from the test analysis.

- 1) The SRR of SIS is greatly affected by the different seismic waves. The SRP of SIS under the near fault ground motion is worse than that under the far fault ground motion.
- 2) The earthquake intensity has great influence on the seismic reduced performance of SIS, and SRR increases with increasing earthquake intensity and SRP is better. And it is more obvious for the near fault ground motion.
- 3) The effect of multi-dimensional seismic excitation on SRP of SIS is not clear, and the two kinds of curves are very close. But the SRR under the 3DSE is slightly higher than that under the 2DSE.
- 4) The equivalent period of SIS mainly distributes at a range of natural period that the effect of near fault ground motion is significant. Therefore, its SRR is less than that under far fault ground motion. And the SRP under the far fault ground motion is better. These results are consistent with the results obtained from response spectra analysis.
- 5) The SRP also is affected by the characteristics of seismic wave, and it should be further studied.

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