PRELIMINARY ANALYSIS OF ISOLATED RAISED FLOORS

S. CUI and M. BRUNEAU

ABSTRACT

To protect the non-structural components in critical facilities (such as hospitals), focusing in particular on the key sensitive components on the floor of a room, the combined solution of stiffening the structure and isolating the floor is proposed. One-story and three-story stiffened shear frames were considered as examples for the purpose of conducting different analyses. Models for each analysis case, both coupled and uncoupled models, were set up in SAP2000, and subjected to three spectra compatible acceleration time histories generated by using the TARSCTHS code. ISO-Base platforms by WorkSafe Technologies were selected as the isolators of interest in this early phase of the project. The preliminary analysis results show a decrease of the relative displacement of the isolated raised floor with respect to the corresponding base frame floor, and an increase of the lateral deformation of the base shear frame floor, when the isolated raised floor mass is increased. A theoretical explanation for the results is provided for the observed trends. The limited comparison of the analysis results between the coupled model and uncoupled model indicates that the uncoupled model results are conservative and could be used for the design of isolated raised floors.

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INTRODUCTION

Vargas and Bruneau (2006a, 2006b) presented a structural fuse concept where passive energy dissipation (PED) devices are designed such that all seismically induced damage is concentrated on the PED devices, allowing the primary structure to remain elastic during seismic events. The structures designed under this concept are stiff, leading to a decrease in drift demands on the non-structural components. However, the acceleration demands on the non-structural component can increase using this system.

To protect the non-structural components in critical facilities (such as hospitals), the key sensitive components on the floor of a room, the authors propose a combined solution of stiffening the structure and isolating the floor.

ISO-Base platforms (Kemeny 2003, Vargas and Bruneau 2006b) by WorkSafe Technologies, assemblies of Ball-in-Cone (BNC) isolators, were adopted as isolators to reduce the acceleration response of the non-structural component on the floor of a room. This kind of isolator is designed to limit horizontal accelerations to 0.1g.

This paper presents the preliminary analytical results for isolated raised floor system. Both coupled and uncoupled model are analyzed using SAP2000 V9.0 (CSI 2004) as part of a limited parametric study. Nonlinear time history analysis results are presented for the response quantities of interest. Theoretical explanation is provided for observed trends of response quantities. Time history analysis results are compared between coupled and uncoupled model.

PRELIMINARY ANALYSIS OF ISOLATED RAISED FLOORS

Modeling

A one-story one-bay single-degree-of-freedom (SDOF) base frame with an isolated raised floor on top is considered. For this purpose, a typical SDOF design sample from Vargas and Bruneau (2006a) is adopted as the base frame. Consider this frame as a shear frame with flexible columns and an infinitely rigid beam. The mass of this shear frame M_{sf} is 0.35 kN·s^2/mm (2 kip·s^2/in). The initial lateral stiffness K_{isf} is 9.43 kN/mm (282.26 kip/in), and its yield strength V_{ysf} is 714.39 kN (160.61 kip). The natural vibration period of this SDOF frame T_{nsf} is 0.53 s. The post yielding stiffness ratio is α_{sf} = K_{psf}/K_{isf} =0.25, where K_{sfp} is the frame lateral stiffness after yielding. The equivalent linear viscous damping ratio of the shear frame is 5%.

For isolators, each unit of ISO-Base platform consists of two sets of BNC isolators interconnected by a plank assembly. ISO-Base platforms have a small height, 76 mm (3 in), which is a key factor for isolated raised floor system design. For each BNC isolator (Vargas and Bruneau 2006b), the bearing plates have a spherical central area and a conical surface to govern the isolator behavior. The conical plate has a diameter of 213 mm (8.375 in). The center spherical area radius R is 127 mm (5 in) and the cone slope is 1:10 (i.e., a 6 degree angle β to the horizontal) with a maximum displacement capacity of 178 mm (7 in). ISO-Base platforms have bilinear-elastic lateral force-displacement behavior. When the balls are within the spherical central area, the ISO-Base platforms have linearly elastic lateral force-displacement behavior. When the balls are in the conical surface, the lateral restoring force corresponds to a constant value V_{yi}, which is also the maximum lateral force that can be reached when the balls are in the spherical central area. Assume the weight of the isolated raised floor is W_i, then the isolator initial stiffness K_{ii} and the maximum lateral restoring force V_{yi} can be calculated in proportion to W_i as $K_{ii}= W_i/(2R)$ and $V_{yi}=K_{ii}(2R\sin\beta)$ respectively. To limit the lateral deformation of

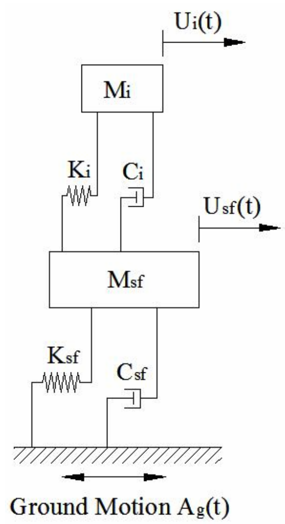

Figure 1. Coupled model

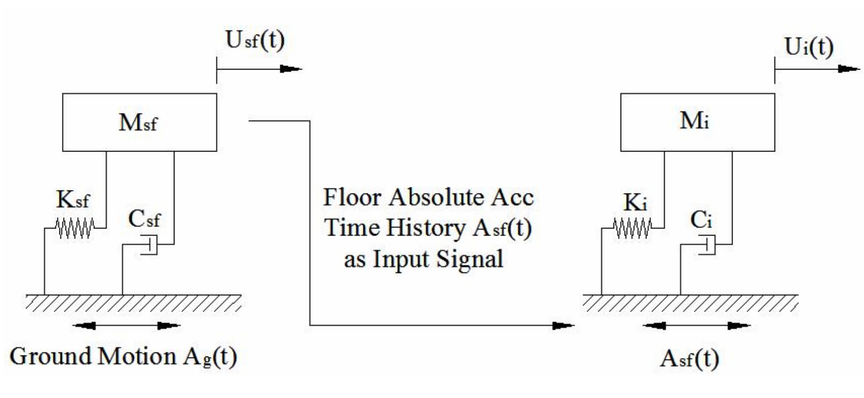

Figure 2. Uncoupled model: (a) Base SDOF shear frame; (b) Isolated raised floor

the ISO-Base platform within its deformation capacity (7 in), extra viscous damping can be added to the ISO-Base platform plates by using rubber liners.

The program SAP2000 V9.0 (CSI 2004) was used to model and analyze the system mentioned above. The shear frame mass and isolated raised floor mass were idealized as masses lumped at their corresponding floor levels. Wen plastic link element and multi-elastic link element were applied to simulate the lateral inelastic hysteretic property of the shear frame and the bilinear-elastic force-displacement behavior of the isolators respectively. Linear viscous damper link element was used to simulate the damping mechanisms in the system. The coupled model analysis approach is shown in Fig. 1. In Fig. 1 C_{sf} represents the 5% viscous damping in the shear frame, calculated as $2M_{sf}\zeta_{sf}\omega_{nsf}$ (ζ_{sf}, 5% linear viscous damping ratio in the frame; and ω_{nsf}, natural vibration frequency of the SDOF shear frame), C_i stands for the linear viscous damping of isolators, which can be calculated as $2M_i\zeta_i\omega_{ni}$ (M_i, mass of the SDOF isolated raised floor system; ζ_i, linear viscous damping ratio in isolated floor system; and ω_{ni}, natural frequency of the SDOF isolated raised floor system, $2\pi/(1.01\text{ s})$), and $A_g(t)$ represents the ground seismic motion.

For comparison with the coupled model analysis approach above, uncoupled model analysis approach was also constructed as shown in Fig. 2, which consists of two SDOF systems. The first SDOF system, base shear frame was modeled as a Wen plastic link element in parallel with a linear viscous damper link element. The other SDOF system consists of the isolated raised floor lumped mass, a multi-elastic link element in parallel with a linear viscous damper link element. Because Fig. 1 and Fig. 2 are for illustration of the model analysis approach, the heights of the base shear frame and the isolated raised floor system are not to scale.

A system consisting of a multi-degree-of-freedom (MDOF) base shear frame with a same isolated raised floor on each floor level is also considered. For the three-story base shear frame considered, each story is identical to the one-story one-bay frame considered above. The coupled model is built as three successive stories of the coupled model shown in Fig. 1. The difference lies only in the linear viscous damping ratio for the isolated raised floor system. In uncoupled model of this system, the MDOF base shear frame was modeled as three successive stories of the SDOF base shear frame

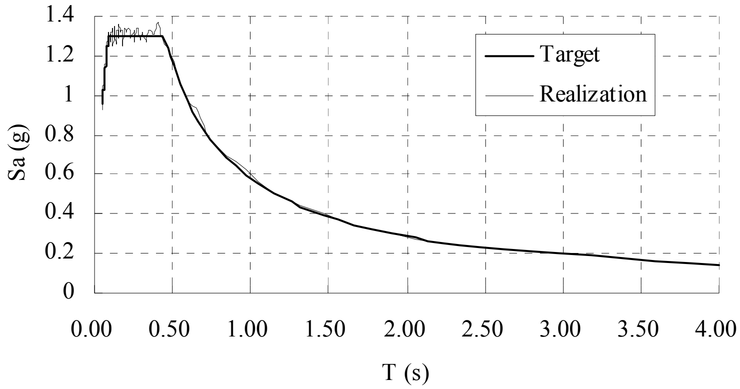

Figure 3. Average elastic response spectrum of realization vs target elastic response spectrum (ζ=5%)

shown in Fig. 2(a). In uncoupled analysis approach, this MDOF system is analyzed, and the resulting floor absolute acceleration time histories at each level are used as input to analyze the response of another SDOF system modeling isolated raised floor which is the same approach as shown in Fig. 2(b).

Spectra Compatible Acceleration Time Histories

An elastic response spectrum was defined in accordance with the NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures (FEMA 2004) for Sherman Oaks, California, and site soil-type class B, the site of the Multidisciplinary Center for Earthquake Engineering Research (MCEER) Demonstration Hospital. The design spectral accelerations for this site are S_{DS}=1.3g, and S_{D1}=0.58g for 2% probability of exceedance in 50 years. For this spectrum, T_s is 0.45 s, and T_0 is 0.09 s. Three response spectra compatible acceleration time histories are generated by using the Target Acceleration Response Spectra Compatible Time Histories (TARSCTHS) Code, by Papageorgiou et al. (1999). The comparison between the average of the three elastic response spectra for 5% of critical damping corresponding to the three response spectra compatible acceleration time histories and the target NEHRP 2003 elastic response spectrum is shown in Fig. 3.

Parametric Study Using Time History Analysis

A parametric study was applied to investigate the effects of different mass ratios of the isolated raised floor mass to the corresponding base shear frame floor mass on the response of the base frame floor and isolated raised floor. Parametric study is conducted for the coupled and uncoupled models. Analysis Case 1 consists of the sample SDOF base shear frame with an isolated raised floor on top. Analysis Case 2 consists of the MDOF base shear frame with the same isolated raised floor on each floor level as mentioned above. For all selected mass ratios, the linear viscous damping ratio of the isolated raised floor system is 21% and 30% for analysis Case 1 and 2 respectively.

For all selected mass ratios, the natural vibration periods and natural vibration modes for the coupled systems in analysis Case 1 are shown in Table 1. In Table 1, T_1 and T_2 are the natural vibration periods of the coupled system as shown in Fig. 1, ϕ_{11} and ϕ_{21} are elements of the first

Table 1. Natural periods and modes of coupled systems

R_1 (%)	R_2 (%)	T_{ni} (s)	T_{nsf} (s)	T_1 (s)	T_2 (s)	ϕ_{11}	ϕ_{21}	ϕ_{12}	ϕ_{22}
Analysis Case 1									
0.15	0.155	1.01	0.53	1.01	0.53	0.0006	1	-2.655	1
4.76	5	1.01	0.53	1.02	0.52	0.018	1	-2.721	1
9.09	10	1.01	0.53	1.03	0.52	0.036	1	-2.788	1
16.67	20	1.01	0.53	1.05	0.51	0.068	1	-2.921	1
23.08	30	1.01	0.53	1.06	0.50	0.098	1	-3.051	1
28.57	40	1.01	0.53	1.08	0.49	0.126	1	-3.178	1
33.33	50	1.01	0.53	1.10	0.49	0.151	1	-3.304	1
37.50	60	1.01	0.53	1.11	0.48	0.175	1	-3.427	1
41.18	70	1.01	0.53	1.13	0.47	0.197	1	-3.550	1
44.44	80	1.01	0.53	1.14	0.47	0.218	1	-3.670	1
47.37	90	1.01	0.53	1.16	0.46	0.237	1	-3.790	1
50.00	100	1.01	0.53	1.17	0.46	0.256	1	-3.908	1

mode vector ϕ_1, ϕ_{12} and ϕ_{22} are elements of the second mode vector ϕ_2. The first subscript "1" corresponds to the lateral degree of freedom of the frame floor and the first subscript "2" represents the lateral degree of freedom of the isolated raised floor. R_1 is the mass ratio $M_i/(M_i+M_{sf})$, R_2 is the mass ratio M_i/M_{sf}. From Table 1, note that the natural periods of the integrated system become more separate than those of the base frame and isolated raised floor system if they are treated as an SDOF system respectively.

Nonlinear time history analysis results for response quantities of interest are shown in Table 2, where U_{ri}, A_{absi}, U_r, and A_{abs} represent the average maximum values of the relative displacement of the isolated raised floor with respect to the corresponding base shear frame floor, the absolute acceleration of the isolated raised floor, the relative displacement of the frame floor with respect to the shaking ground, and the absolute acceleration of the frame floor respectively. $U_{ri}D$, $A_{absi}D$, U_rD and $A_{abs}D$ represent the ratios of difference in U_{ri}, A_{absi}, U_r, and A_{abs} between results from coupled model and uncoupled model (results from coupled model minus corresponding results from uncoupled model for each specific quantity) to the corresponding results from coupled model respectively.

From Table 2, note that while the linear viscous damping ratio for the isolated raised floor system remains the same and the mass ratio R_1 (or R_2) increases, U_{ri}, A_{absi}, U_r, and A_{abs} remain (or almost remain) the same value for the uncoupled model. And for coupled model, U_{ri}, A_{absi} and A_{abs} decrease and U_r increases. From the "Difference" columns in Table 2, it can be found that the difference between results from different analysis models become more and more significant and the results obtained from uncoupled model are conservative. Therefore, the results from uncoupled model can be used as demands for design of isolated raised floors.

Factors Influencing Observed Trends in Response

From Table 1, note that the natural vibration periods, T_1 and T_2, fall on the constant velocity region (i.e., no smaller than T_s) of the response spectrum as shown in Fig. 3. As in Vargas and Bruneau (2006a), the equal displacement theory is adopted here. Therefore, for the coupled system in Fig. 1 subjected to seismic ground motion, the equation of motion can be expressed as Eq. 1.

Table 2. Time history analysis results

R_1 (%)	R_2 (%)	Results from Coupled Model U_{ri} (mm)	A_{absi} (mm/s^2)	U_r (mm)	A_{abs} (mm/s^2)	Results from Uncoupled Model U_{ri} (mm)	A_{absi} (mm/s^2)	U_r (mm)	A_{abs} (mm/s^2)	Difference $U_{ri}D$ (%)	$A_{absi}D$ (%)	U_rD (%)	$A_{abs}D$ (%)
Analysis Case 1													
0.15	0.155	160.8	2755.4	64.5	3896.6	160.8	2755.4			0.0	0.0	0.0	-0.1
4.76	5	160.3	2672.6	64.3	3804.9	162.6	2695.2			-1.4	-0.8	-0.4	-2.5
9.09	10	158.5	2661.2	63.8	3740.9	162.6	2695.2			-2.6	-1.3	-1.2	-4.2
16.67	20	158.0	2605.3	64.8	3604.3	162.6	2694.4			-2.9	-3.4	0.4	-8.2
23.08	30	158.5	2542.3	66.0	3494.3	162.6	2694.7			-2.6	-6.0	2.3	-11.6
28.57	40	158.8	2482.1	66.8	3417.8	162.6	2694.9	64.5	3898.9	-2.4	-8.6	3.4	-14.1
33.33	50	158.5	2412.2	67.8	3362.7	162.6	2694.9			-2.6	-11.7	4.9	-15.9
37.50	60	156.2	2350.0	69.1	3312.2	162.6	2694.9			-4.1	-14.7	6.6	-17.7
41.18	70	152.1	2274.1	70.6	3299.0	162.6	2694.9			-6.8	-18.5	8.6	-18.2
44.44	80	148.1	2214.6	72.6	3310.6	162.6	2694.9			-9.8	-21.7	11.2	-17.8
47.37	90	144.0	2175.3	74.9	3303.8	162.6	2694.9			-12.9	-23.9	13.9	-18.0
50.00	100	140.5	2139.7	77.5	3257.8	162.6	2694.9			-15.7	-25.9	16.7	-19.7
Analysis Case 2, 1st Story													
0.15	0.155	93.7	2210.6	119.6	3070.1	93.7	2213.6			0.0	-0.1	0.0	-0.2
9.09	10	91.2	1988.3	122.9	2954.3	103.6	2221.7			-13.6	-11.7	2.7	-4.1
23.08	30	69.6	1776.0	130.0	2807.5	103.9	2223.3			-49.3	-25.2	8.0	-9.6
33.33	50	53.6	1546.9	152.1	2453.4	103.9	2223.5	119.6	3075.7	-93.8	-43.7	21.4	-25.4
37.50	60	49.3	1467.1	160.3	2328.9	103.9	2223.8			-110.8	-51.6	25.4	-32.1
44.44	80	43.9	1438.1	170.4	2327.7	103.9	2223.5			-136.4	-54.6	29.8	-32.1
50.00	100	40.6	1419.4	180.6	2219.7	103.9	2223.5			-155.6	-56.7	33.8	-38.6
Analysis Case 2, 2nd Story													
0.15	0.155	148.6	2693.7	197.6	2382.5	148.8	2697.7			-0.2	-0.2	0.0	-0.2
9.09	10	137.7	2523.0	201.9	2290.8	156.7	2752.1			-13.8	-9.1	2.1	-4.2
23.08	30	111.8	2287.0	216.7	2112.8	156.7	2753.1			-40.2	-20.4	8.8	-13.0
33.33	50	99.1	2048.3	253.2	2143.0	156.7	2753.1	197.6	2386.6	-58.2	-34.4	22.0	-11.4
37.50	60	90.9	1908.0	267.5	1958.8	156.7	2753.6			-72.3	-44.3	26.1	-21.8
44.44	80	75.9	1603.0	285.8	1747.0	156.7	2753.4			-106.4	-71.8	30.8	-36.6
50.00	100	64.8	1430.3	298.7	1587.5	156.7	2753.4			-142.0	-92.5	33.8	-50.3
Analysis Case 2, 3rd Story													
0.15	0.155	166.9	2767.3	214.4	2370.1	167.1	2778.0			-0.2	-0.4	0.0	-0.1
9.09	10	157.2	2615.4	219.5	2246.6	174.5	2789.9			-11.0	-6.7	2.3	-5.6
23.08	30	134.9	2389.4	238.8	2138.7	174.5	2790.7			-29.4	-16.8	10.2	-11.0
33.33	50	126.0	2113.0	283.7	2067.6	174.5	2791.0	214.4	2372.9	-38.5	-32.1	24.4	-14.8
37.50	60	117.1	1929.6	302.0	2037.6	174.5	2791.2			-49.0	-44.6	29.0	-16.5
44.44	80	96.0	1628.9	324.9	1906.0	174.5	2791.0			-81.7	-71.3	34.0	-24.5
50.00	100	81.0	1558.3	341.1	1768.1	174.5	2791.0			-115.4	-79.1	37.2	-34.2

$$\left\{\begin{matrix} M_{sf} & 0 \\ 0 & M_i \end{matrix}\right\}\left(\begin{matrix}\ddot{U}_1\\ \ddot{U}_2\end{matrix}\right) + \left\{\begin{matrix} C_{sf}+C_i & -C_i \\ -C_i & C_i\end{matrix}\right\}\left(\begin{matrix}\dot{U}_1\\ \dot{U}_2\end{matrix}\right) + \left\{\begin{matrix}K_{sf}+K_i & -K_i\\ -K_i & K_i\end{matrix}\right\}\left(\begin{matrix}U_1\\ U_2\end{matrix}\right) = -\left\{\begin{matrix}M_{sf} & 0\\ 0 & M_i\end{matrix}\right\}\left\{\begin{matrix}1\\ 1\end{matrix}\right\}\ddot{U}_g \qquad (1)$$

Assuming classical damping in this system, applying modal analysis as in Chopra (2001), using the spectra acceleration values in Fig. 3 and absolute sum (ABSSUM) modal combination rule give the trends of peak values of the response quantities of interest in terms of contributions from natural

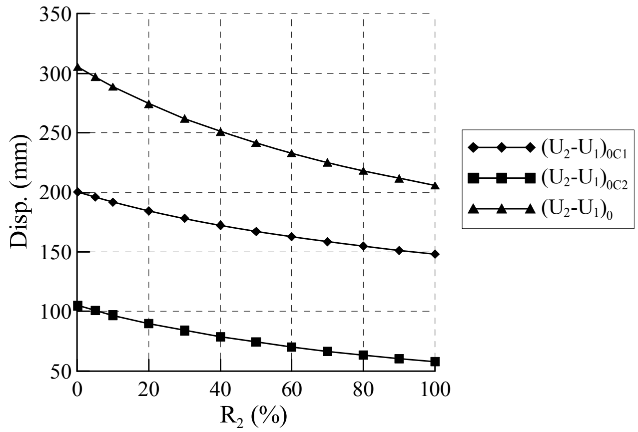

Figure 4. $(U_2-U_1)_0$ trend for analysis case 1

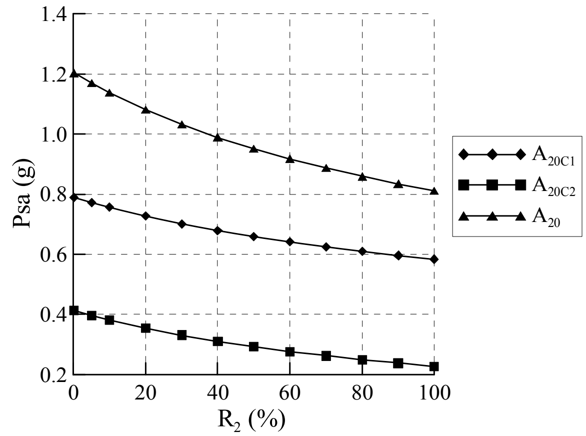

Figure 5. A_{20} trend for analysis case 1

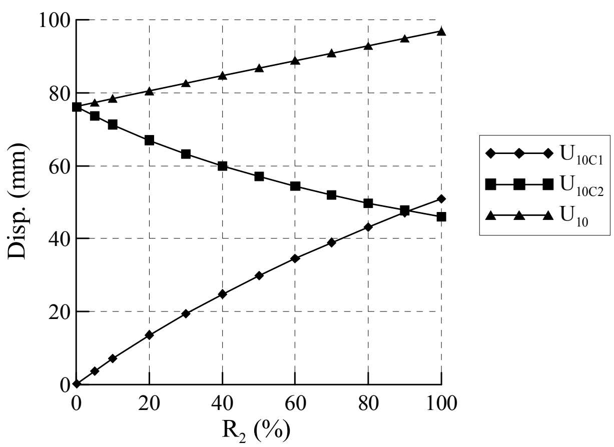

Figure 6. U_{10} trend for Analysis Case 1

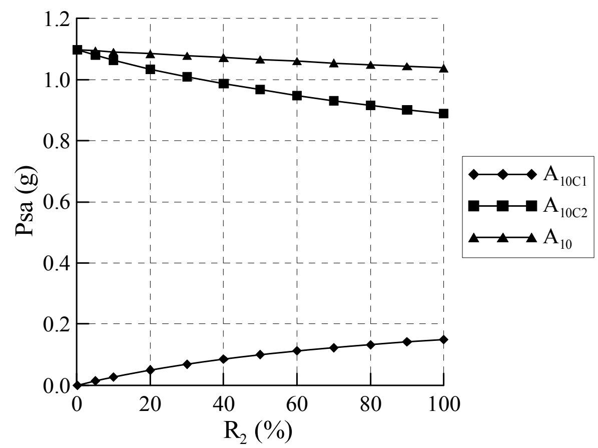

Figure 7. A_{10} trend for Analysis Case 1

vibration Mode 1 and Mode 2 as shown in Fig. 4 through Fig. 7, where the subscript "c1" and "c2" in the figure legend indicate the contributions from Mode 1 and Mode 2 respectively. The mass ratio affects the natural vibration periods, which then affects the response quantities. From these figures, the same trends for the response quantities of interest, U_{ri}, A_{absi}, U_r and A_{abs}, are found as above.

CONCLUSIONS

A combined solution of stiffening the structural frame and isolating room floors is proposed to protect the seismic sensitive non-structural components. From preliminary analytical work, the peak values of the relative displacement of the isolated raised floor with respect to the corresponding frame floor and the absolute acceleration of both the isolated raised floor and the base frame floor decrease, and the peak value of the relative displacement of the frame floor with respect to the shaking ground increases with increasing of the mass ratio. It can also be found that the results from uncoupled model are conservative and can be used as demands for the design of isolated raised floor systems.

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