Sliding Fragility of Restrained and Unrestrained Block-Type Nonstructural Components

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SUMMARY:
This paper aimed to evaluate the seismic response of block-type freestanding nonstructural components in direct contact with a horizontal supporting surface and subjected to base excitation. To establish fragility curves for the sliding response of these components, many acceleration time-history inputs are generated using the artificial motion generation program "SIMQKE". Restraining these components has been carried out using four cables. In most cases, it has been found that such restrain reduce the displacements and accelerations considerably. The results show that fragility curves for restrained blocks are sensitive mainly to the dynamic coefficient of friction and to the ratio of the vertical component of the cable forces to the weight of the block. Furthermore, it has been found that fragility curves have direct relation to the maximum magnitudes of the pseudo-velocity spectrum curves.

Keywords: nonstructural component, seismic design, sliding fragility

1. INTRODUCTION

Nonstructural components of a building are those systems, parts, elements, or components that are not part of the structural system, but are subjected to the building dynamic environment causes by, for example, an earthquake. They include architectural elements such as ceiling tiles and internal partitions, and infrastructure systems such as fire-suppression, water and wastewater distribution, electric power, telecommunications, and heating, ventilating, and air-conditioning systems. This research aimed to evaluate the seismic response of free standing block-type nonstructural components in direct contact with horizontal supporting surfaces. Block-type components include all nonstructural components that their behaviors are essentially that of a rigid body, and as such can then be appropriately modeled. These components might be either restrained or unrestrained.

Effects of recent earthquakes have clearly shown that the overall seismic hazard to structures cannot be efficiently reduced unless the design of nonstructural components receives the same degree of consideration as primary structural members. In past earthquakes, the level of damages sustained by nonstructural components was in most cases higher than that usually considered acceptable (Naeim & Lobo, 1998; Naeim, 2000; Miranda et. al., 2003). Many buildings that remained structurally sound after the earthquake lost their functionality due to damage to their nonstructural components. While this is always inconvenient and undesirable for any kind of construction, it is certainly unacceptable for critical facilities, such as hospitals, that need to be functional during and after an earthquake. Examples of such damages had been seen in the 1971 San Fernando, 1994 Northridge, 1995 Kobe, and 2003 Bam earthquakes. Economic loss due to seismic nonstructural damage can also be considerable. A case in point is the seismic damage sustained by buildings during the 1994 Northridge earthquake. With the loss of approximately $18.5 billion due to building damage, nonstructural damage accounted for about 50% of this total (Kircher, 2003). The 1994 Northridge earthquake clearly demonstrated the inadequacy of previous practices that address only life safety and collapse prevention for the structure.

The former observations indicate in a straightforward way that there is a need to investigate the seismic behavior of nonstructural components in order to assess their vulnerability under seismic events. By identifying the expected performance level of this type of components, potential retrofitting measures can be suggested and implemented in order to improve their seismic performance. This can be determined by either shake table testing, experience data, or analysis. For equipment that needs to remain functional after the seismic event, some codes have suggested the use of a testing procedure to evaluate their performance. Such procedure need to satisfy the design and evaluation requirements provided that the substantiated seismic capacities equal or exceed the seismic demands (IBC, 2009; ASCE 7, 2010). Furthermore, such seismic qualification procedure ought to be based upon recognized testing standards, such as AC 156 (ICC, 2010).

At the moment, many third-world countries lack the necessary facilities to implement the new code requirements mentioned above. To meet these requirements, the present paper suggests a numerical simulation procedure to be used to evaluate the performance of nonstructural components on statistical bases. This procedure is based on generating artificial records that can be used to establish fragility curves that are necessary for identifying the performance-level for a given component.

2. NONSTRUCTURAL FRAGILITIES

Many authors had investigated the rigid body motion of block-type components but most of the early contributions have focused on the rocking response (Yim & Chopra, 1980; Ishiyama, 1982; Spanos & koh, 1991; Shenton, 1996; Zhu & Soong, 1998). The conditions under which the response is only of sliding nature have been also investigated (Shenton & Jones, 1991; Shenton, 1996; Chong & Soong, 2000; Choi & Tung, 2002; Lopez Garcia & Soong, 2003a; Chaudhuri & Hutchinson, 2006). It has been found that sliding response occurs only for a certain range of values of the width-to-height ratio of the block. Otherwise, other types of response occur. Furthermore, the equations of motion of the restrained block under sliding response have been developed (Lopez Garcia & Soong, 2003b).

In this paper, fragility curves have been established for the sliding response of unrestrained and restrained nonstructural components. Such an approach is usually used to remove uncertainties that usually associated with seismic records. In order to form fragility functions it is first necessary to specify measures of damage. Although a variety of such measures are possible, this study has followed previous works in choosing "excessive displacement" as an indicator for the failure of an unrestrained block (Chong & Soong, 2000). On the other hand, two limit states are considered for restraint blocks; namely, breakage of the restraining cables and excessive absolute acceleration (Lopez Garcia & Soong, 2003b).

3. APPROACH OF RESEARCH

The method used in this paper is based on the SIMQKE software program. The acceleration histories were scaled to horizontal peak base accelerations (HPGA) ranging from 0.10 g to 1.50 g with 0.10 g increments. For each of these cases, 90 artificial records have been generated. The input data has been applied to blocks supported on surfaces with different dynamic coefficients of friction (μ_d) that range from 0.1 to 0.5. Furthermore, the effect of vertical peak base accelerations (VPGA) has been investigated by using five different vertical-to-horizontal-acceleration ratios (*k*) that ranges from zero to 0.67. By determining the equation of sliding motion and solving it numerically, displacement and acceleration time histories for the sliding block are obtained.

In this paper, two groups of artificial acceleration histories have been used. The first includes the Iranian standard design response spectrum (BHRC, 2005), the normalized response spectrum suggested by the 2010 edition of AC156 (ICC, 2010) and the response spectrum that suggested by Shakib (Shakib, 2007). The second includes eight local earthquake records belong to soil type B in the

USGS classification system. These records have different magnitudes and occurred in different parts of Iran. Details of these records are given in Table 3.1.

Table 3.1. Records Used In This Paper (BHRC)

Earthquake	Record No.	Epicentre Distance (km)	Horizontal Components		Vertical Components	
			PGA (g)	PGV (cm/sec)	PGA (g)	PGV (cm/sec)
Naghan	1-1054	5	0.808	67.359	0.580	42.614
Tabas	1-1084	54	0.790	91.697	0.683	33.615
Zarrat	16-142	27	0.317	12.964	0.109	3.843
Qasem Abad	01-1754	60	0.141	12.946	0.076	2.811
Kaboodar Ahang	01-2754	55	0.082	5.924	0.068	2.986
Zanjiran	9-1502	12	1.068	31.117	0.941	15.893
Siyahoo	01-2325	25	0.213	5.978	0.137	3.101
Sirch	01-1913	7	0.592	83.891	0.784	95.295

4. RESULTS

4.1. Performance of Unrestrained Blocks under Different Seismic Excitations

The behavior of unrestraint blocks under different seismic events has been investigated. The eight records given in Table 3.1., the Iranian standard design response spectrum (BHRC, 2005), and the response spectrum suggested by AC156 (ICC, 2010), have been applied to the unrestraint block. The block average relative peak displacements, which are obtained from the ninety peak displacements obtained from the ninety acceleration time history inputs for different coefficients of friction (μ_d) are shown in Table 4.1.

Table 4.1. Average Displacements of 90 Artificial Acceleration Records Scaled to 1g with k=2/3 for the Unrestrint Blocks. All Units in cm.

μ_d	Naghan	Tabas	Zarrat	Qasem Abad	Kaboo-dar Ahang	Zanjir-an	Siyah-oo	Sirch	IS 2800	ICC
0.1	6.15	15.56	5.63	9.31	11.97	3.39	6.27	21.44	34.52	44.92
0.2	6.15	16.32	6.24	7.49	14.46	3.68	8.16	24.66	31.76	40.46
0.3	5.63	14.88	4.54	4.30	12.80	2.56	7.03	21.99	27.53	36.28
0.4	3.94	11.54	2.68	2.07	9.44	1.45	5.00	16.36	22.81	30.02
0.5	2.51	8.08	2.89	1.00	6.39	0.78	3.28	11.21	17.08	22.65

It is clear from these results that the peak displacement increases as the vertical and horizontal peak accelerations increase. Furthermore, increasing the coefficients of friction results in a reduction of displacements. Moreover, comparing the results given by the eight seismic records, it is found that the highest results are those related to Sirch and Tabas Earthquakes. By investigating the properties of these two and other earthquakes, it is found that such results have direct relation to the maximum magnitudes of the pseudo-velocity spectrum curves.

Among all the investigated records, it is clear that the ICC record yields the highest displacements and therefore can be used as an envelope for the nonstructural components test.

4.2. Fragility Curves for Unrestraint Blocks

In this section, Fragility curves for three response spectrum curves are presented. The Iranian standard design response spectrum (BHRC, 2005), the normalized response spectrum suggested by AC156 (ICC, 2010) and Shakib's response spectrum (Shakib, 2007) are used in this study. In this section, samples of fragility curves are shown in Fig. 4.1.

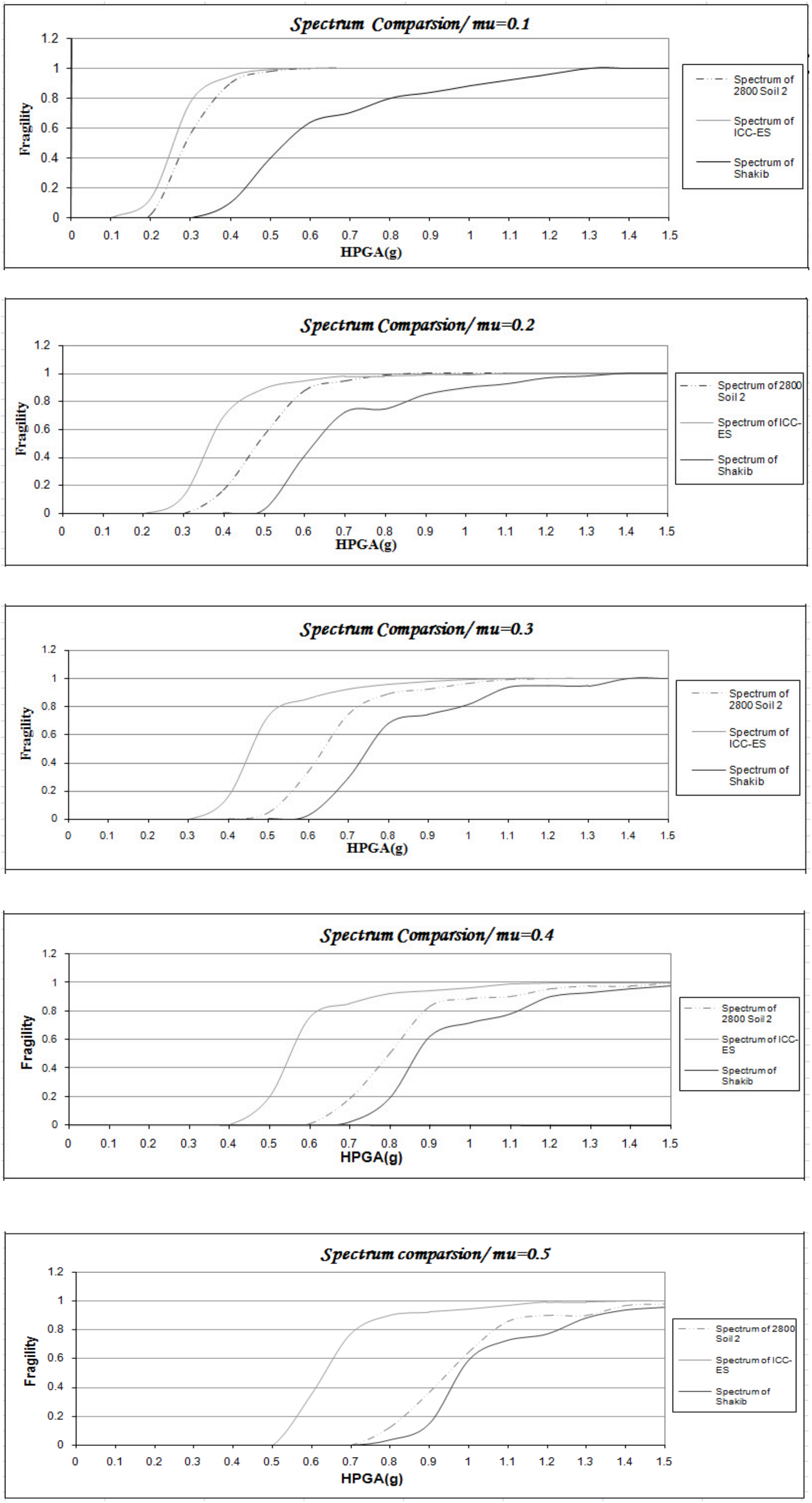

Figure 4.1. Fragility curves for free-standing blocks. Failure threshold = 2 cm.

4.3. Performance of Restrained Blocks under Different Seismic Excitations

The restrained system is shown in Fig. 4.2. It has been shown that for a given base acceleration history, the response of the restrained block depends on four parameters: the dynamic coefficient of friction (μ_d), the vertical-to-horizontal-acceleration ratio (*k*), the would-be natural period of the system in absence of friction (T_{eq}) and the ratio of the vertical component of the cable forces to the weight of the block (β) (Lopez Garcia & Soong, 2003b).

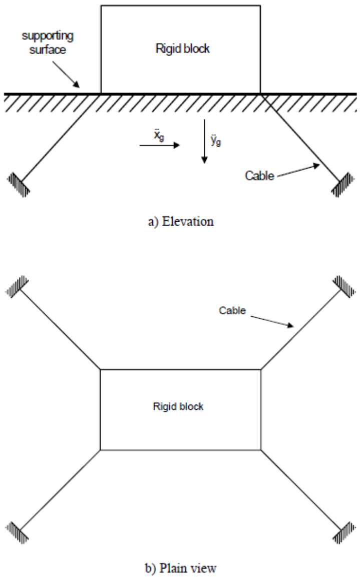

Figure 4.2. Rigid block attached to cables

In order to get more insight into the influence of the above mentioned parameters, many acceleration records have been applied to restraint blocks. Based on the results obtained in previous sections, the two acceleration records that yield the highest displacements are chosen to serve this purpose; namely, the Tabas and Sirch earthquake records. The results for these two records are given for the four cases given by Table 4.2. :

By taking the breakage of the restraining cables as the failure criteria for the restraint block, the maximum allowable displacement for each of the above mentioned cases depends only on β and T_{eq}. For the four cases investigated in this section, these are given in Table 4.2.

Table 4.2. Maximum Allowable Displacements for Restraint Blocks.

Case No.	β	T_{eq}	The maximum allowable displacement (cm)
1	0.7	0.05	0.0218
2	0.7	0.2	0.348
3	1.0	0.05	0.0311
4	1.0	0.2	0.497

The block average relative peak displacements, which are obtained from the ninety peak displacements obtained from the ninety acceleration time history inputs for different coefficients of friction (μ_d) are shown in Table 4.3.

Table 4.3. Average Displacements of 90 Artificial Acceleration Records Scaled to 1g with k=2/3 for the Restraint Blocks. All Units in cm.

μ_d	Tabas				Sirch			
	1st case	2nd case	3rd case	4th case	1st case	2nd case	3rd case	4th case
0.1	10.88	10.88	9.33	9.33	15.94	15.94	14.08	14.08
0.2	7.93	7.93	5.60	5.60	11.13	11.13	7.67	7.67
0.3	4.27	4.27	2.38	2.38	5.63	5.63	2.98	2.98
0.4	1.91	1.91	0.77	0.77	2.35	2.35	0.88	0.88
0.5	0.77	0.77	0.21	0.21	0.87	0.87	0.23	0.23

Compared these results with those given in Table 4.1., it is clear that displacements are smaller in magnitude. Therefore, restrained schemes are the obvious choice for block-type nonstructural components whose failure mode is given by excessive horizontal displacements. Furthermore, and in clear similarity to the unrestraint cases, it has been found that the probability of failure depends strongly on (μ_d). The effect of higher (β) is also noticeable in reducing displacements. On the other hand, and as shown in Table 4.2, the role of T_{eq} is less important.

4.4. Fragility Curves for Restraint Blocks

Fragility curves were also obtained for different values of the parameters involved. In this section, samples of fragility curves for the Tabas and Sirch earthquakes are shown in Figs. 4.4. and 4.5.

By studying the results given by Figs 4.3. and 4.4., it can be seen that fragility curves depend strongly on (μ_d) and only marginally on the other parameters. The interval within $0 < \text{fragility} < 1$ is very narrow and close to the vertical line. Moreover, fragility curves for $k = 0$ are always below those for $k \neq 0$. Therefore, fragility assessments ignoring vertical accelerations are unconservative. Furthermore, similar to the unrestraint cases, it is found that displacements have direct relation to the maximum magnitudes of the pseudo-velocity spectrum curves.

5. SUMMARY AND CONCLUTIONS

In this paper, the performance of a rigid block resting on a rigid supporting base subjected to horizontal and vertical base excitations, has been studied. Five parameters have been studied in this research. They are the coefficient of dynamic friction (μ_d), the HPGA, the VPGA, the would-be natural period of the system in absence of friction (T_{eq}) and the ratio of the vertical component of the cable forces to the weight of the block (β). From the results obtained, it is seen that the coefficient of dynamic friction (μ_d) is the most important coefficient influencing displacements and accelerations. Furthermore, from studying the results obtained from this paper, it is found that fragility curves have direct relation to the maximum magnitudes of the pseudo-velocity spectrum curves.

Results of this study indicate that restraints are very effective in reducing horizontal displacements. Therefore, restrained schemes are the obvious choice for block-type nonstructural components whose failure mode is given by excessive horizontal displacements. In the case of components whose failures modes are given by excessive displacements and excessive absolute accelerations, restraints can also be used. In these cases, the controlling failure mode is given by breakage of the restraints. Post-tension forces, which significantly influence the corresponding fragility curves, can then be conveniently selected so that the resulting probability of failure is low enough. Furthermore, it is always advisable to use both HPGA and VPGA in evaluating the fragility curves.

Within the range of data tested in this paper, it seems that ICC test is a suitable tool for testing nonstructural components. However, more detailed study need to be carried out to establish the performance level associated with this test.

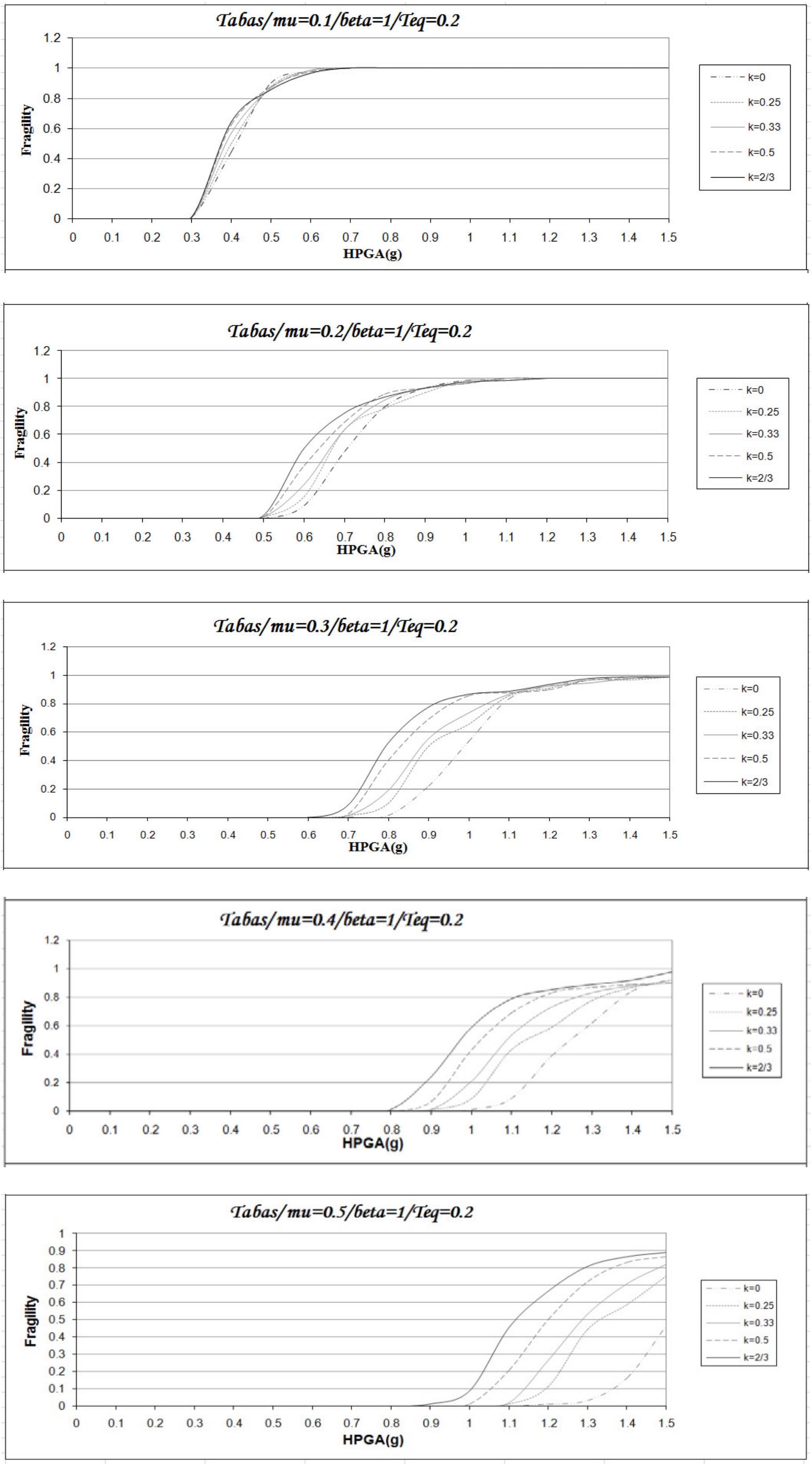

Figure 4.3. Fragility curves for restrained blocks subjected to Tabas earthquake record for β=1.0 and T_{eq}=0.20 with different values for μ and k.

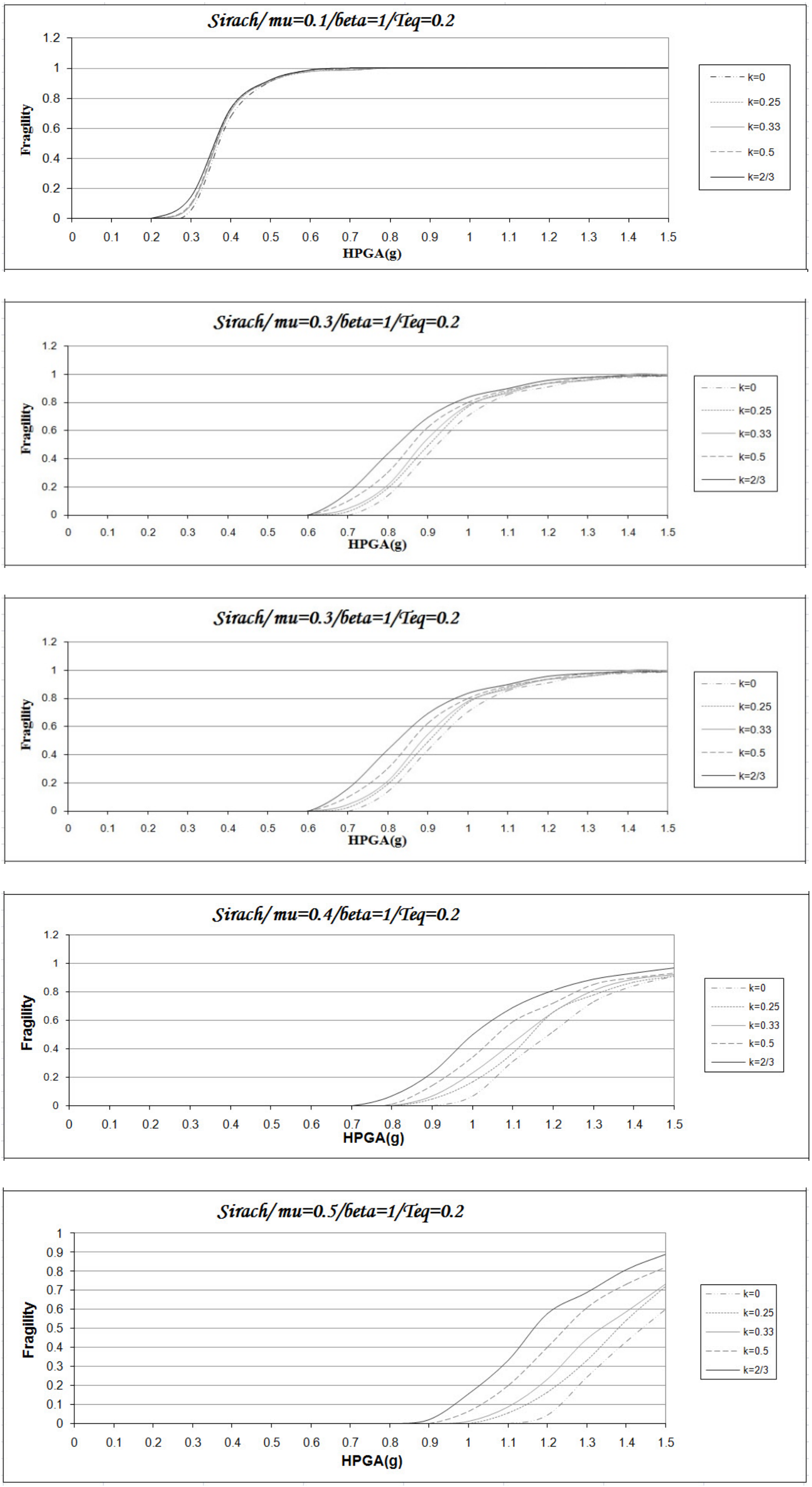

Figure 4.4. Fragility curves for restrained blocks subjected to Sirch earthquake record for β=1.0 and T_{eq}=0.20 with different values for μ and k.

AKCNOWLEDGEMENT
The authors wish to thank the Iranian strong motion network (ISMN) for providing them with the earthquake records used in this paper.

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