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THE GENERATION OF EARTHQUAKE DAMAGE PROBABILITY CURVES FOR BUILDING FACILITIES IN TAIWAN

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ABSTRACT: This paper describes earthquake vulnerability curves for nonstructural components developed from hospital and school buildings. Authors investigated nonstructural components damage of 41 hospital buildings in the Chi-Chi earthquake, and concluded data with fragility curves and probability curves. Authors also investigated nonstructural components damage of 56 schools buildings from the Taitung and Heng-Chun earthquake in 2006. Using these curves, the damage prediction for nonstructural components in important buildings can be exercised in Taiwan.

Key Words: hospital, school, fragility curve, nonstructural component, probability curve of repair cost, probability curve of recovery time

INTRODUCTION

In the 1999 Chi-Chi earthquake, Taiwan found that the emergency hospitals' medical capability is inadequate owing to nonstructural component damage inside hospital buildings. (Yao and Lin, 1999). It was later concluded that the importance of nonstructural components' seismic safety in hospitals' continual operation should not be compromised. In order to safeguard the medical capability to execute disaster relief work after an earthquake, a hospital needs to improve the seismic performance of both building structures and its nonstructural components. The same approach should also be applied to school buildings because many of them will be needed to serve as the community shelter after a major earthquake. Also because the nonstructural components in the typical buildings constituted 82%-92% of total investment which could be the main proportion of earthquake damage loss (Taghavi and Miranda , 2003) as shown in Figure 1, the seismic damage of nonstructural components were paid much attention by researchers in order to reduce economic loss in earthquakes.

The damage investigation after an earthquake and the derivation of fragility curves, have increased gradually in the past twenty years. The fragility curves can describe damage probability with peak ground acceleration (PGA) in earthquake engineering community. William (William, 1998) compared the damage of nonstructural components in the Northridge earthquake with that in previous earthquake experience, and generalized a suggestion of seismic performance in nonstructural components. Kuo et al. (Kuo, Hayashi and Kambara, 2004) performed a questionnaire investigation to find out that nonstructural components damage begin to take place at seismic intensity 5+, and the damaged condition rises rapidly at seismic intensity 6. Tien and Pai (Tien and Pai, 2006) built the fragility curve on the ratio of building damage and personnel death. Porter (Porter, 2007) estimated the fragility curve of elevator with the method of Binary Regression Analysis.

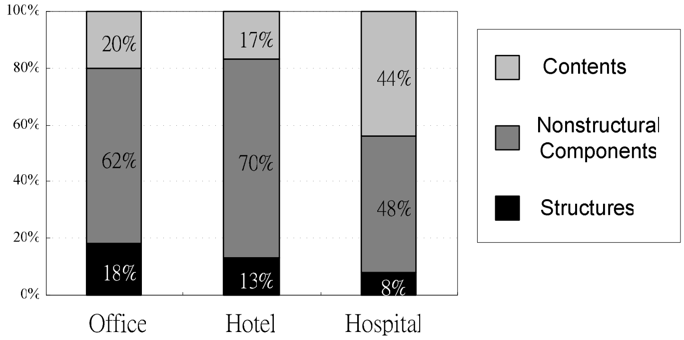


Figure 1 The investment ratio of nonstructural components in buildings

Recently, Yeh (Yeh, 2002) established the Taiwan Earthquake Loss Estimation System (TELES) with local data in Taiwan to estimate the probable damage loss of structures and nonstructural components. However, the fragility curve of nonstructural components in TELES adopts much American materials, lacks of the domestic data of nonstructural components in Taiwan. After the 1999 Chi-Chi earthquake, Taiwan experienced many moderate ones. These earthquakes produce different levels of damage to nonstructural components and we collect and analyze them to produce local nonstructural damage data.

This study describes a nonstructural component database of hospital and school buildings from past earthquakes in Taiwan. It includes data from 3 earthquakes namely, the 1999 Chi-Chi earthquake, Taitung earthquake on April 1st 2006, and the Heng-Chun earthquake on December 26th in 2006. The derived data from questionnaires includes: damage probability curves of different nonstructural components, probability of repair cost, and probability of recovery time of nonstructural components.

METHODOLOGY

According to the Nonstructural Performance Levels of FEMA356 (FEMA, 2000), this study divides the nonstructural components into Architectural Components (A), Mechanical or Electrical or Plumbing Systems/Components (B), and Contents (C). However, the classification of FEMA356 in nonstructural components was not designed specifically for hospitals or schools. In accordance with the building characteristics in Taiwan, this study made a questionnaire of nonstructural components by modifying Table C1-5 through C1-7 of FEMA356. Finally, 4 types of damage description: no damage, slight damage, moderate damage and extensive damage were used for statistical analysis to establish fragility curves for nonstructural components.

The damage condition of nonstructural components was surveyed and their repair cost and recovery time probability curves were also analyzed by using questionnaire data in this study. The algorithms of the log-normal distribution curve fitting were used to plot the corresponding repair cost probability curves.

Selection of samples

This study collected three-component strong motion records of earthquakes from the Central Weather Bureau (CWB). PGA of each building site could be estimated by using the Kriging interpolation.

The selection steps of buildings are as follows:

1. Selecting the hospitals with in-patient beds from 736 hospitals, and schools from Taitung and

Pingtung.

2. The seismic intensity 5 of CWB (I=5) is based on the Weber-Fechner rule as Eq.1. and indicated an acceleration (α_I) range from 80 ~ 250 gal.

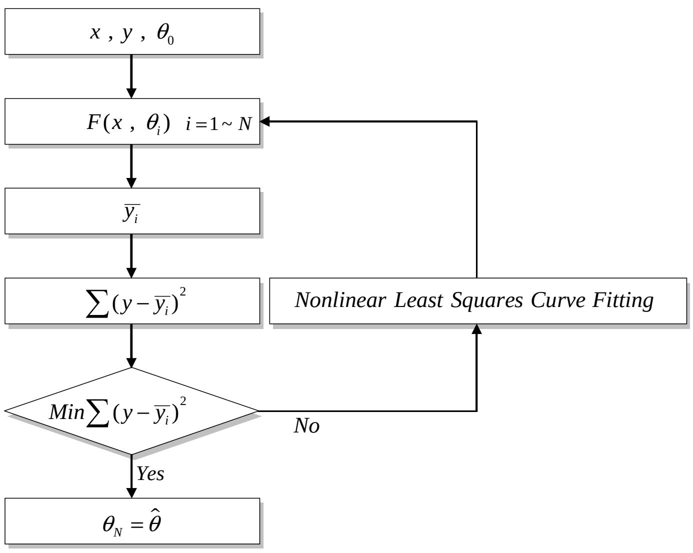
$$\alpha_I = 0.8(10^{\frac{I-1}{2}} \sim 10^{\frac{I}{2}}) \tag{1}$$

If I=5.5 is used to separate intensity 5- and intensity 5+, we can calculate from Eq.1. to know that the separation acceleration is 140 gal.

3. Select buildings in which the seismic intensity exceeded 5+（PGA > 140 gal）.
4. Telephone, inquiry and site visit them which can help to fill in the questionnaire

PROBABILITY CURVES OF NONSTRUCTURAL COMPONENTS

The probability curve in this study adopts the method of probability theory and Survival Analysis that MCEER puts forward in the technical report (MCEER, 1999) to investigate the damaged situation of nonstructural components of earthquakes in hospitals and schools. Analysis steps are as shown in Fig. 2 to calculate the average (λ) and standard deviation (ζ) value:



$$x=\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix}\ ,\quad y=\begin{Bmatrix} y_1 \\ y_2 \\ y_3 \end{Bmatrix}\ ,\quad \theta=\begin{Bmatrix} \lambda \\ \zeta \end{Bmatrix}$$

Figure 2 Process of non-linear regression

Based on λ and ζ value, the probability curve could be estimated as Fig. 3 ~ 5.

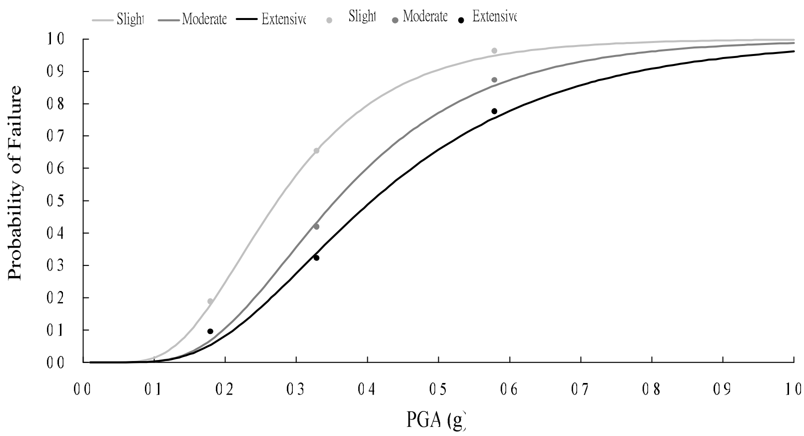


Figure 3 Fragility curves

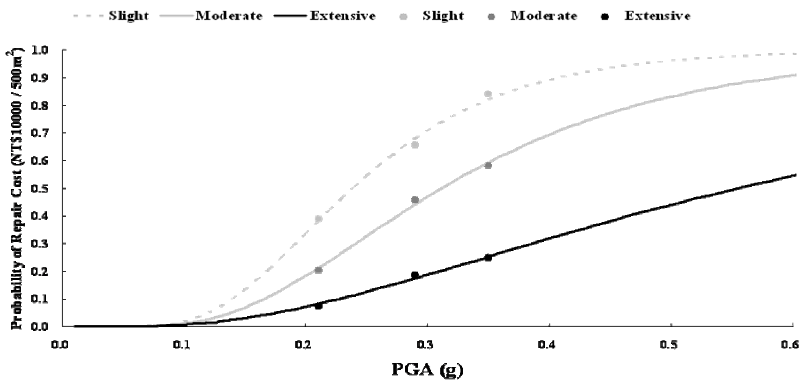


Figure 4 Probability curves of repair cost

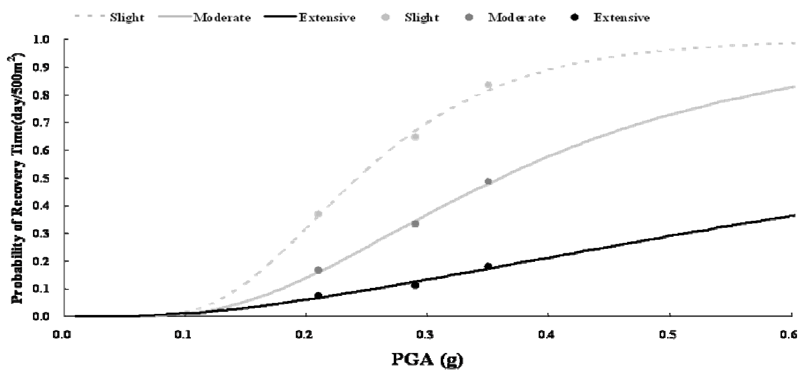


Figure 5 Probability curves of recovery time

APPLICATION

Hospital Buildings – Fragility curves

The λ and ζ value for nonstructural components in hospitals were estimated, as Table 1 shows. Every fragility curve of nonstructural components can be shown as in Fig.6~8.

Table 1 The λ and ζ value of each nonstructural components in hospitals

No.	Nonstructural components	λ			ζ		
		Slight	Moderate	Extensive	Slight	Moderate	Extensive
A-1	Exterior Walls	-1.3	-1.03	-0.9	0.46	0.46	0.51
A-2	Glazing	-0.85	-0.7	-0.41	0.54	0.61	0.55
A-3	Partitions	-1.34	-0.8	-0.17	0.57	0.54	0.63
A-4	Suspending Ceilings	-1.13	-1	-0.88	0.46	0.47	0.48
A-5	Parapets	-1.03	-0.42	-0.14	0.46	0.61	0.74
A-6	Stairs	-0.89	-0.44	0.25	0.47	0.61	0.75
A-7	Doors	-0.85	-0.62	0.25	0.44	0.56	0.75
B-1	Elevators	-0.67	-0.52	-0.27	0.43	0.38	0.23
B-2	HVAC Equipment	-0.68	-0.42	-0.16	0.63	0.61	0.62
B-3	Boiler	-0.4	-0.23	-0.23	0.55	0.45	0.45
B-4	Mainframe of Ice Water	-0.66	-0.16	0.28	0.4	0.62	0.74
B-5	Cooling Tower	-0.59	-0.42	0.25	0.53	0.61	0.75
B-6	Air Conditioner Duct	-0.69	-0.41	0.25	0.44	0.55	0.75
B-7	Piping	-0.86	-0.39	-0.21	0.58	0.46	0.5
B-8	Fire Sprinkler Systems	-0.42	-0.16	0.28	0.61	0.62	0.74
B-9	Fire Alarm Systems	-0.58	-0.58	0.25	0.49	0.49	0.75
B-10	Emergency Lighting	-0.71	-0.71	-0.62	0.32	0.32	0.33
B-11	Light Fixtures	-0.78	-0.61	-0.41	0.51	0.53	0.55
B-12	Sanitary Equipment	-0.69	-0.53	0	0.44	0.4	0
C-1	Computer Systems	-0.77	-0.53	-0.4	0.37	0.4	0.39
C-2	Desktop Equipment	-1.39	-0.98	-0.78	0.53	0.39	0.39
C-3	File Cabinets	-1.2	-1	-0.49	0.48	0.47	0.7
C-4	Book Shelves	-1.19	-0.88	-0.69	0.39	0.35	0.43
C-5	Art Objects	-0.95	-0.95	-0.55	0.5	0.5	0.45
C-6	Medical Equipment	-1.06	-0.95	-0.14	0.46	0.5	0.74

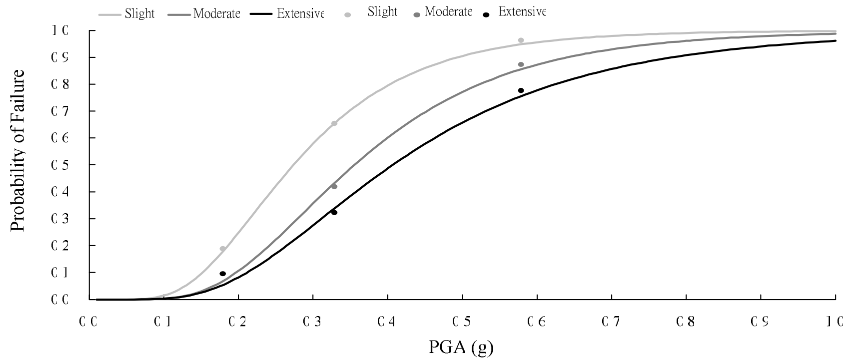


Figure 6 Fragility curve of exterior wall (A-1)

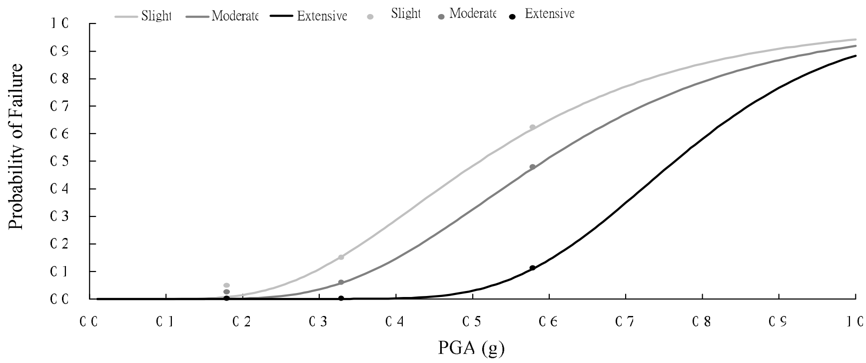


Figure 7 Fragility curve of elevator (B-1)

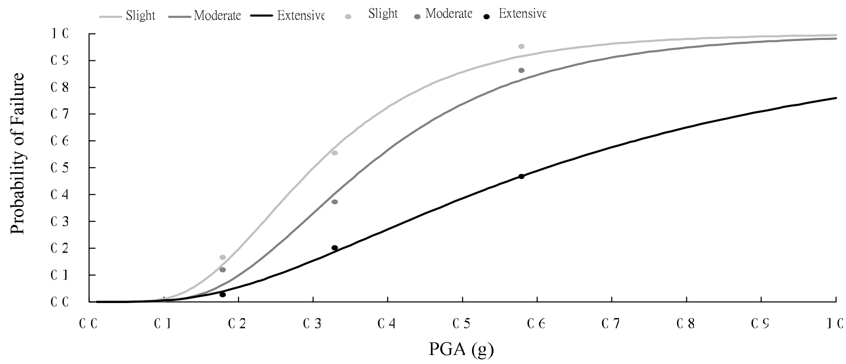


Figure 8 Fragility curve of file cabinets (C-3)

Hospital Buildings – Repair cost

This study divided the repair cost of nonstructural components in hospital buildings into 3 parts, medical equipment, machine equipment, and information equipment. Total repair cost was defined as the repair cost sum of all equipment.

In order to use the data for all hospitals, a floor area of 500 m^2 of the hospital building was treated as a denominator to normalize the repair cost. The repair cost calculation result of nonstructural components and estimated parameters in hospital buildings were shown in Table 2. Analysis steps can be found in Yao's and Tu's researches (Yao et al, 2008 and Tu et al, 2009). The results were shown as Fig. 9 ~12.

Table 2 Repair cost of nonstructural components in hospital buildings

		Medical Equipment	Machine Equipment	Information Equipment	Total Equipment
Slight	Interval (NT$10000/500m^2)	0.00-0.99	0.00-0.99	0.00-0.99	0.00-0.99
	Average (NT$10000/500m^2)	0.03	0.02	0.03	0.20
	λ	-0.7742	-0.7788	-0.8737	-1.0981
	ζ	0.8744	0.5117	0.5203	0.5554
Moderate	Interval (NT$10000/500m^2)	1.00-9.99	1.00-4.99	1.00-4.99	1.00-19.99
	Average (NT$10000/500m^2)	3.19	3.72	2.83	9.19
	λ	-0.6031	-0.7196	-0.6991	-0.8023
	ζ	0.7717	0.4487	0.4191	0.3531
Extensive	Interval (NT$10000/500m^2)	10.00-80.00	5.00-210.00	5.00-80.00	20.00-220.00
	Average (NT$10000/500m^2)	30.68	88.78	18.52	97.33
	λ	0.1121	-0.3286	0.0788	-0.3286
	ζ	0.8387	0.4501	0.6780	0.4501

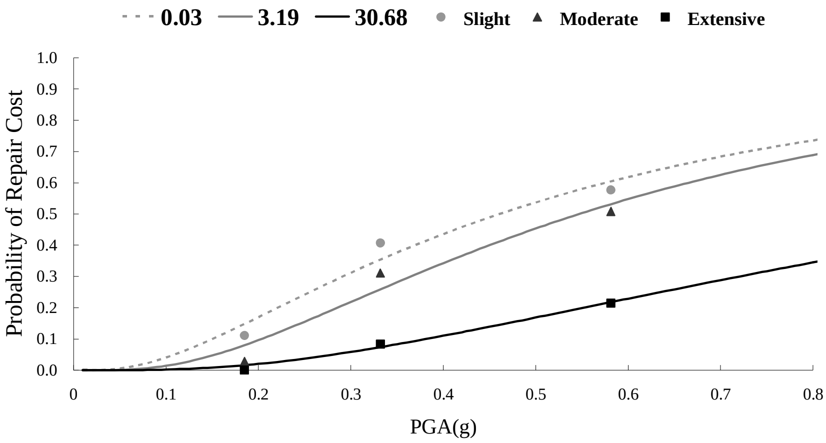


Figure 9 Repair cost probability curves of medical equipment

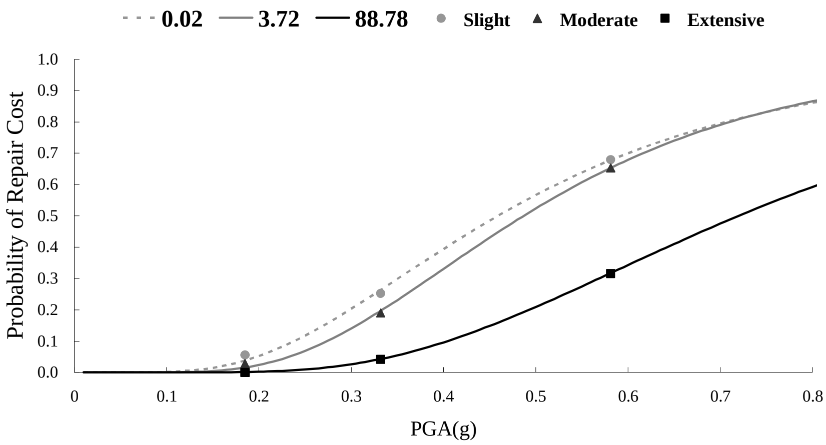


Figure 10 Repair cost probability curves of machine equipment

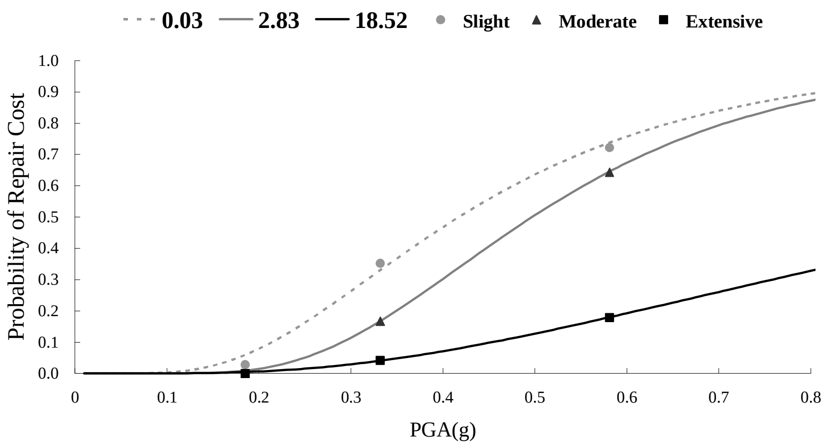


Figure 11 Repair cost probability curves of information equipment

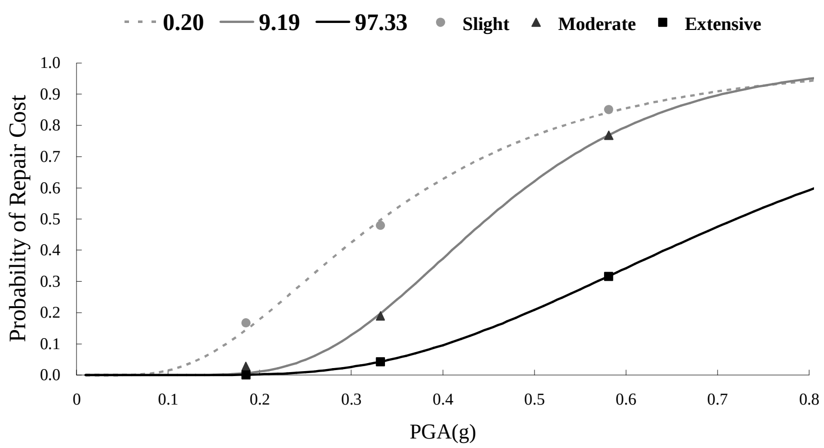


Figure 12 Repair cost probability curves of total equipment

From Fig. 9, the repair cost probability curves of medical equipment defined at slight, moderate, and extensive damage level corresponds to 0.03, 3.19, and 30.68 (NT$10000/500m^2) respectively. The probabilities on PGA 0.40g (seismic intensity 7) indicated repair cost of 44%, 34%, and 1% as slight, moderate, and extensive respectively.

In the same approach, the repair cost probability curves of machine equipment, information equipment, and total equipment could be estimated respectively shown as shown Fig.10~Fig.12.

School Buildings – Fragility curves

The λ and ζ value for nonstructural components in schools were estimated and is shown in Table 3..

Table 3 The λ and ζ value of each nonstructural components in school buildings

No.	Nonstructural components	λ			ζ		
		Slight	Moderate	Extensive	Slight	Moderate	Extensive
1	Exterior Walls	-1.3261	-1.0165	-0.7701	0.4522	0.5338	0.6300
2	Partitions	-1.2098	-0.8173	------	0.4719	0.3648	------
3	Suspending Ceilings	-1.1157	-0.9853	-0.8810	0.4305	0.4658	0.4176
4	Parapets	-0.7753	0.0000	0.0000	0.5120	0.0000	0.0000
5	Doors	-0.1859	1.8371	------	0.8915	2.3518	------
6	Sanitary Equipment	-0.7927	0.0000	------	0.3192	0.0000	------
7	Computer Systems	-1.0388	-0.9017	-0.7927	0.2052	0.3128	0.3192
8	Desktop Equipment	-1.2190	-0.8395	-0.2844	0.2217	0.4188	0.6686
9	File Cabinets	-1.1285	-0.9266	-0.8350	0.2140	0.2754	0.2541
10	Book Shelves	-1.0890	-0.6576	-0.3949	0.3769	0.5270	0.6015

Every fragility curve of nonstructural components can be shown as in Fig.13~15.

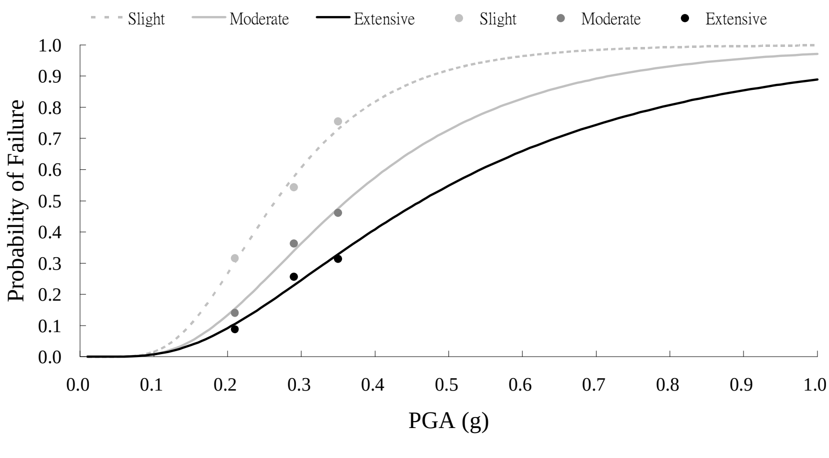


Figure 13 Fragility curves of Exterior Walls (1)

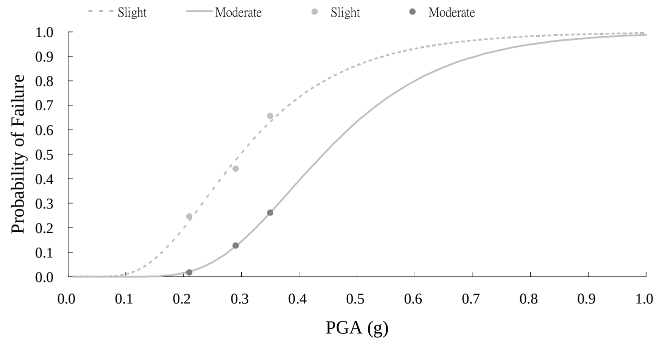


Figure 14 Fragility curves of Partitions (2)

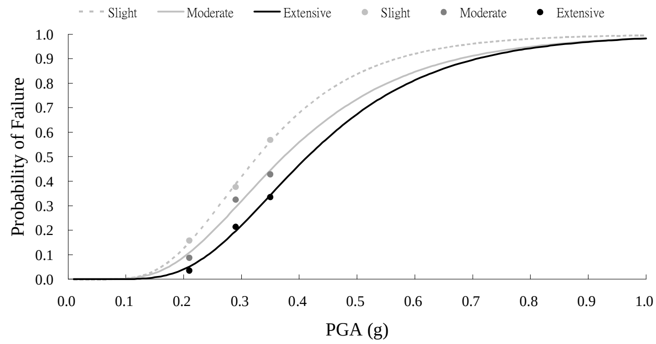


Figure 15 Fragility curves of Suspending Ceilings (3)

School Buildings – Repair cost and Recovery time

This study surveyed the repair cost and recovery time of nonstructural components in school buildings with 3 items only: exterior walls, partitions, and suspending ceilings. Total repair cost and recovery time were defined as the sum of all 3 items in repair cost or recovery time.

In order to apply to all schools, a floor area of 500 m^2 of school buildings was treated as a denominator to normalize the repair cost. The repair cost and recovery time of nonstructural components and estimated parameters in school buildings were shown as Table 4.

Table 4 The λ and ζ value of each nonstructural components in school buildings

	Nonstructural components	λ			ζ		
		Slight	Moderate	Extensive	Slight	Moderate	Extensive
Repair Cost	Exterior Walls	-1.2467	-0.8530	-0.2616	0.4384	0.6043	0.7890
	Partitions	-0.9064	0.2243	0.7140	0.5307	1.1909	1.1696
	Suspending Ceilings	-1.0383	-0.4432	-0.0829	0.3654	0.7112	0.7235
	Total School	-1.4342	-1.1667	-0.5886	0.4168	0.4922	0.6941
	Nonstructural components	λ			ζ		
		Slight	Moderate	Extensive	Slight	Moderate	Extensive
Recovery Time	Exterior Walls	-1.2269	-0.9122	1.1403	0.4851	0.5708	1.5688
	Partitions	-0.9064	-0.6510	-0.3903	0.5307	0.5482	0.6173
	Suspending Ceilings	-1.0748	-0.6207	0.8563	0.3839	0.5668	0.9365
	Total School	-1.4173	-1.0229	-0.1915	0.4062	0.5406	0.9089

The repair cost and recovery time probability curves were shown as Fig. 16~17.

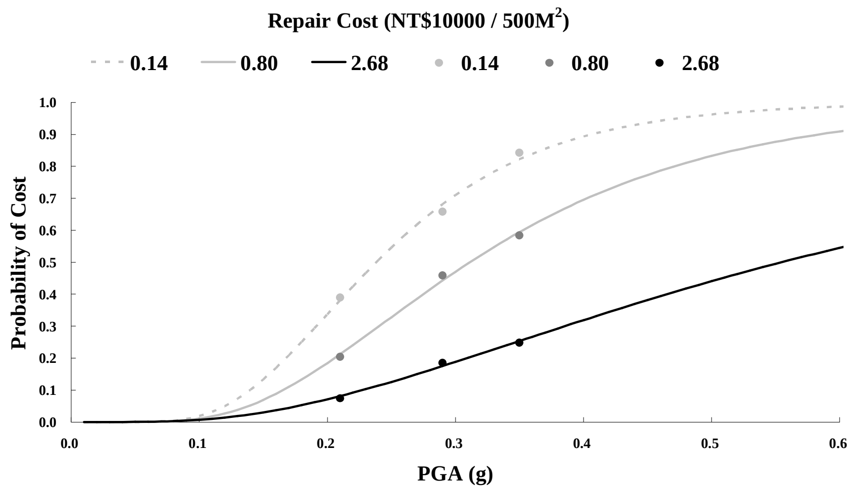


Figure 16 Repair cost probability curve

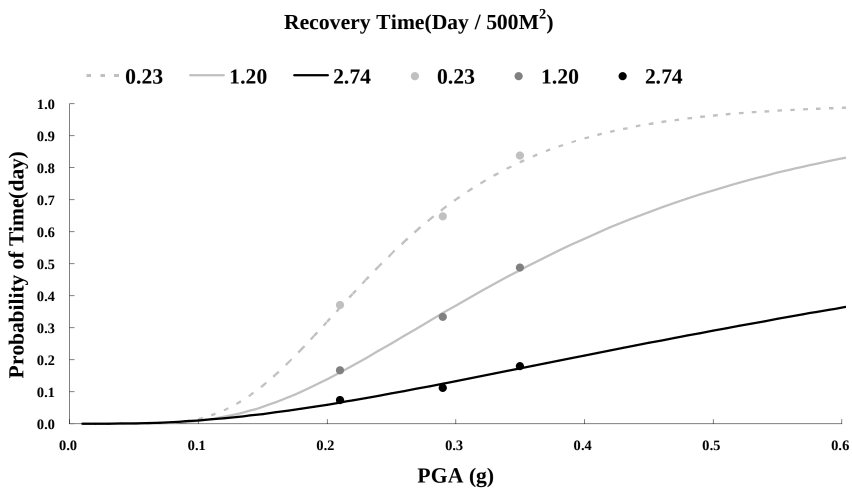


Figure 17 Recovery time probability curves

CONCLUSIONS

The conclusions of this study are as follows:

1. The ζ, standard deviation of fragility curve, was obtained in this study by nonlinear regression. It reflects real site data of each damage component, and is deferent from a fixed value of 0.3 used by other researchers.
2. In hospital, the probability of repair cost is higher when the unit area repair cost is less. As seismic intensity increases, a higher probability of repair cost occurred at the same level of unit area repair cost.
3. The repair costs by definition at the slight level are almost the same and they are close at the moderate level. But, at the extensive level, the repair cost of machine equipment is the largest

subset and the repair cost of information equipment is the smallest one. Therefore, the seismic protection for machine equipment in hospitals should be placed at a higher priority.

4. From fragility curves, the probability of damage of each nonstructural component can be predicted. The probability of repair cost or recovery time of nonstructural components at a certain PGA can be predicted and evaluated from their respective probability curves.

ACKNOWLEDGMENTS

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